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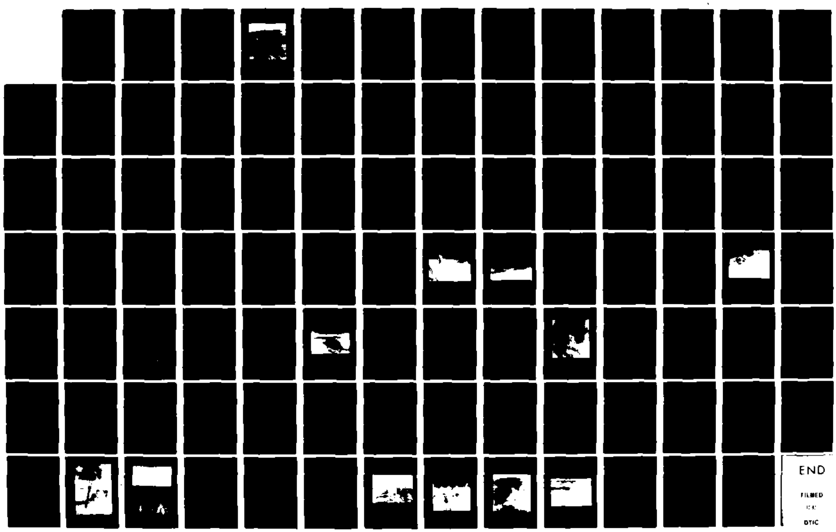

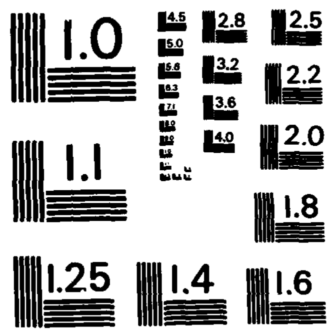

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Report 81-1

A SURVEY OF SOME ARCTIC BEACH ZONES IN SOUTHWEST CORNWALLIS ISLAND, N.W.T.

H.E. Sadler and H.V. Serson

January 1981

Research and Development Branch

Department of National Defence

Canada

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* Now at CRAD, NDHQ, Ottawa, Ontario.

Frontispiece The snow trench at Cape Martyr Station A. The depth of the snow varies from about 30 cm to more than 2 m. The marker poles indicate survey points along the trench.

ABSTRACT

This was a preliminary investigation into the physical processes in the beach zone along an arctic coast with emphasis on the possible damage to scientific equipment by ice action on gravel beaches. Detailed profiles are given of the spring ice on a number of beaches in the area and of the bathymetry and ice morphology at three stations where test cable arrays were laid. The results indicate that a comparatively shallow trench into the frost table below the beach will provide good protection for cables laid across gravel beaches, and that most of the breaks to be expected are probably due to the freezing of the cable onto the bottom surface of the sea ice during tidal changes in level. Additional investigations were made into methods of accelerating the melting of sea ice, on a simple method of obtaining stereophotographs and on the properties of a belt of fresh-water anchor ice which was found along the beaches.

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ABBREVIATIONS, NOTATION AND UNITS

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Abbreviations

CD	Chart Datum
HHWS	Higher High Water Springs
HW	High Water
LLWS	Lower Low Water Springs
LW	Low Water

Notation

g	acceleration due to gravity
I	moment of inertia
L	beam length
M	beam bending moment
S_i	salinity of ice
T	tensile stress
t	ice thickness
Z	height above lower surface of the ice
θ_i	temperature of the ice
ρ_i	density of ice
ρ_w	density of sea water
σ_t	tensile strength of ice

Units

All units are SIU except for the use of kilogram force which is regrettably common in engineering practice. When describing pressure, 1 $kgf.cm^{-2}$ is equivalent to 98.1 kPa.

INTRODUCTION

Research projects and the exploitation of natural resources in the Canadian archipelago often call for equipment such as electrical power cables, pipelines or ship handling gear to be laid across the shore zone. In the region between the heaviest of the grounded ice and the inshore limit of the ice push, such equipment is frequently damaged or destroyed by the movement of sea ice in response to wind or the tidal forces. While large semi-permanent structures such as pipelines can usually be protected by burying them in deep trenches, the use of the large excavating machinery or of the explosive techniques which are necessary may not always be possible or desirable. Small parties, armed with no excavating tools other than pick, shovel and ice-chisel may have to lay cables or other equipment and they should be able to choose locations along the shore line which give some promise that the equipment will not be destroyed before the experiment is finished.

In the course of work in the past few years, parties from DREP have laid a number of armoured cables across arctic beaches. The failure rate has been high, about one third of the cables losing their integrity during the operating period. Unfortunately, the time of failure is the only datum available in most of these cases and we have been unable to correlate them with tidal or wind driven movements of the ice, or to determine the type of failure, whether in lateral compression, in tension or in shear. No obvious pattern of failure exists. Cables laid at one location run from an exposed beach over several off-shore shoals which are frequently cluttered with grounded ice. They have survived for several years while cables laid at a point which is apparently protected from ice action by a high spit of land failed during the first winter. Wilson (Personal Communications, 1978) has proposed a 'male-female' theory of shore geometry which implies that cables laid across the beach at a headland where the shore-line is convex will have a better chance of survival than those laid at the head of a bay where the shore-line is concave. This follows from his suggestion that it is the crushing forces exerted by the edges of blocks of ice as they are tilted and moved shorewards by the periodic tidal changes in water level which are responsible for breaking the cables. The investigation reported here was undertaken to gather more data from several different kinds of beach both to test this theory and to attempt to provide a basis for selection of optimum sites or techniques for running cables.

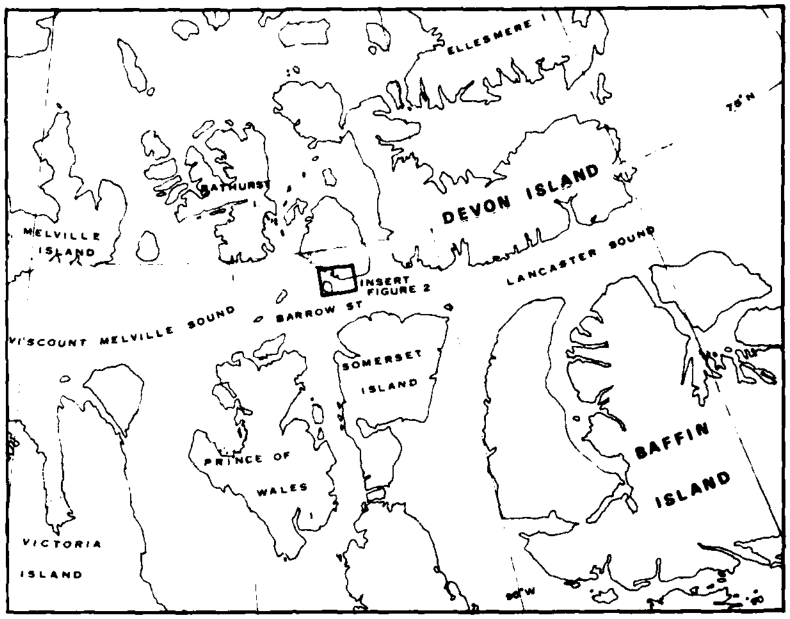


Figure 1. General location map of the arctic islands. The insert marked on the southwest corner of Cornwallis Island indicates the operating area and this is shown in more detail in Figure 2.

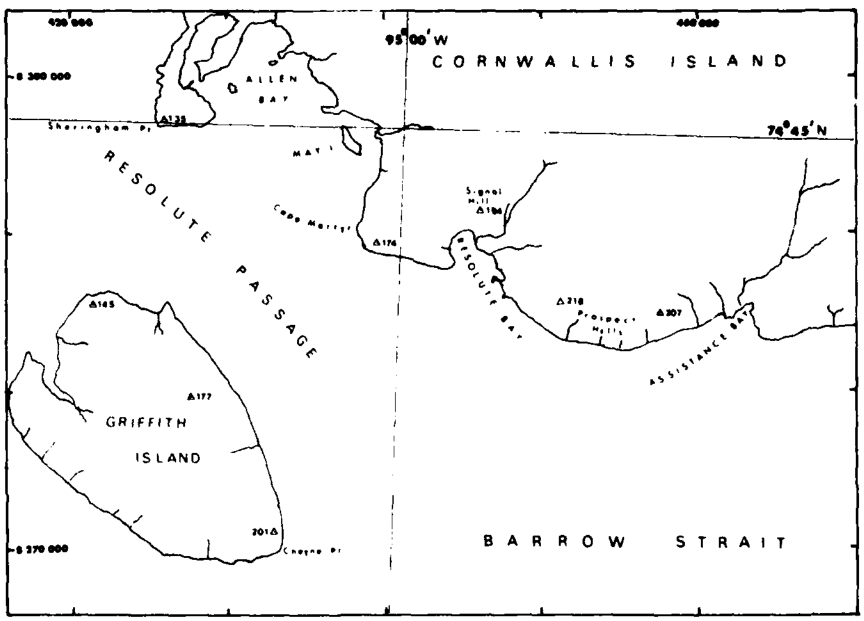


Figure 2. General map of the area examined. We surveyed the shoreline of Cornwallis Island, in greater or lesser detail, from a point 2 km north of Sheringham Point to the head of Assistance Bay, and that of Griffith Island from Cheyne Point to the northern end of the island. Spot heights and grid markings are in metres.

NARRATIVE

The original choice of location was, logically enough, in an area where some data on the destruction of cables were already available and in September 1977 a short reconnaissance was made there. However, it became obvious during the planning stage that any attempt to determine the mechanism of cable breakage would require that we visit the site at least every two or three months throughout the year. The only area in the high arctic to which access could be guaranteed at all seasons was that around Resolute Bay on Cornwallis Island, which is served by scheduled commercial flights from the south, and we selected suitable sites which could be reached at any time from Resolute Bay using off-road vehicles (Figures 1 and 2).

In May 1978 we chose six sites (see Figures 3 to 7) for intensive examination and as locations for the later installation of test cables at a time when the surface was ice-free. At each of these stations we trenched through the snow cover to the upper surface of the ice, digging a trench about 1 m wide and 100 m or more in length running from a point above the HHWS, at right angles to the beach, out to a position where the ice is floating at any state of the tide (Frontispiece). This involved removing an estimated 75 tons of snow and limited the number of stations which could be examined, particularly since the latter half of May 1978 was unusually windy and trenches would often be found refilled with snow at the beginning of a second day's work. We established survey markers on the beach above HHWS and at 15 or 20 points along the trench, the latter being usually located at a high point or an open crack. Holes were bored at each of these points to measure ice thickness, water depth and freeboard, while the height of the upper surface of the ice was determined relative to the beach mark using normal surveying techniques. The measurements were repeated at HW and LW, as predicted for Resolute Bay, and the profile of the ice surface was filled in using intermediate heights and distances obtained by tape measure. At each station we also measured the snow density, the vertical salinity and temperature profiles in the ice, the crushing strength of the ice in situ and the current shear in the water below the ice down to 10 m depth. We also obtained two long cores (10 m) through large grounded floes at the two stations in Resolute Bay, in an attempt to determine the structure of the

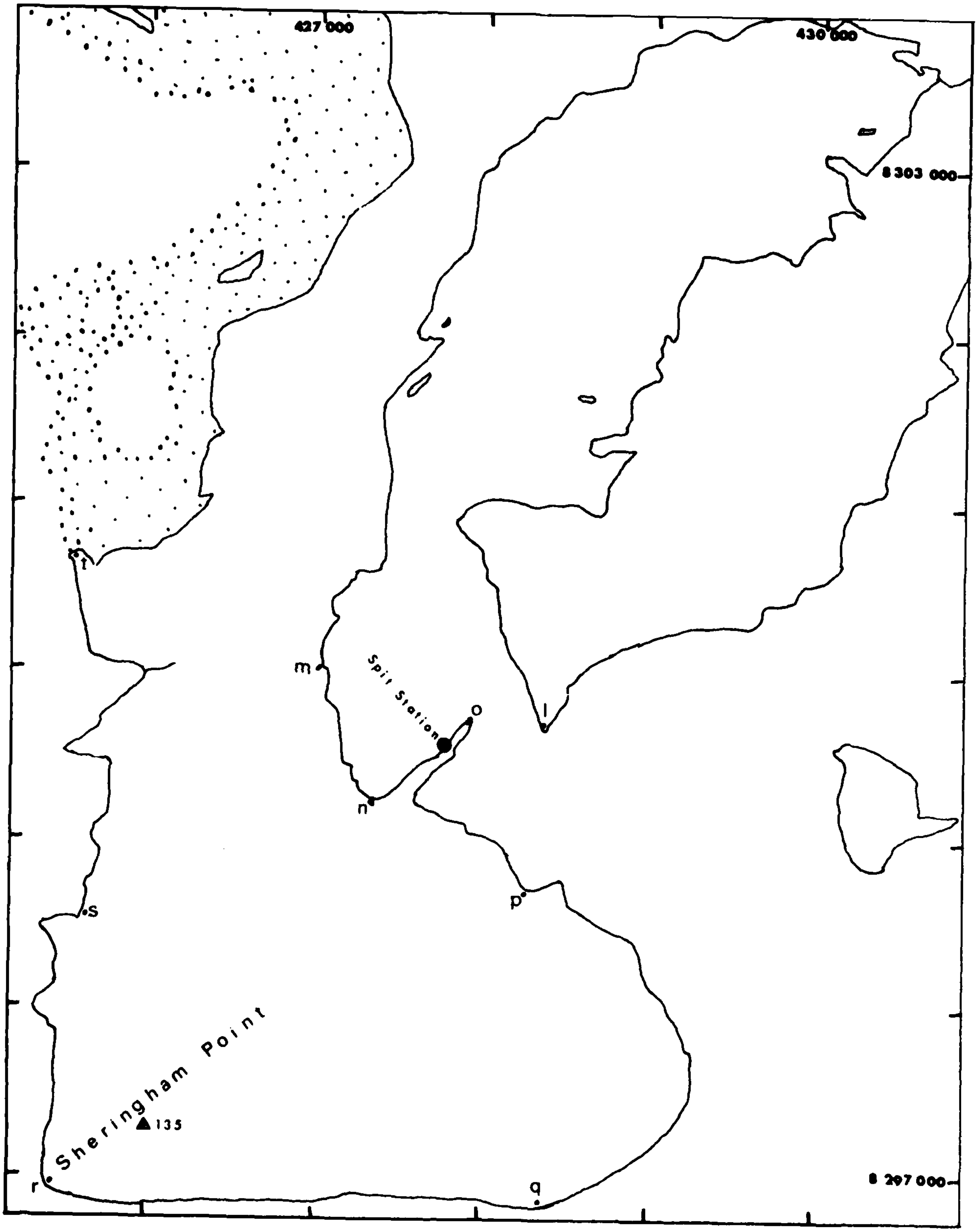


Figure 3. Sheringham Point area showing Spit Station. Grid markings and spot heights are in metres. The lower-case Roman letters indicate reference points used in the field diary.

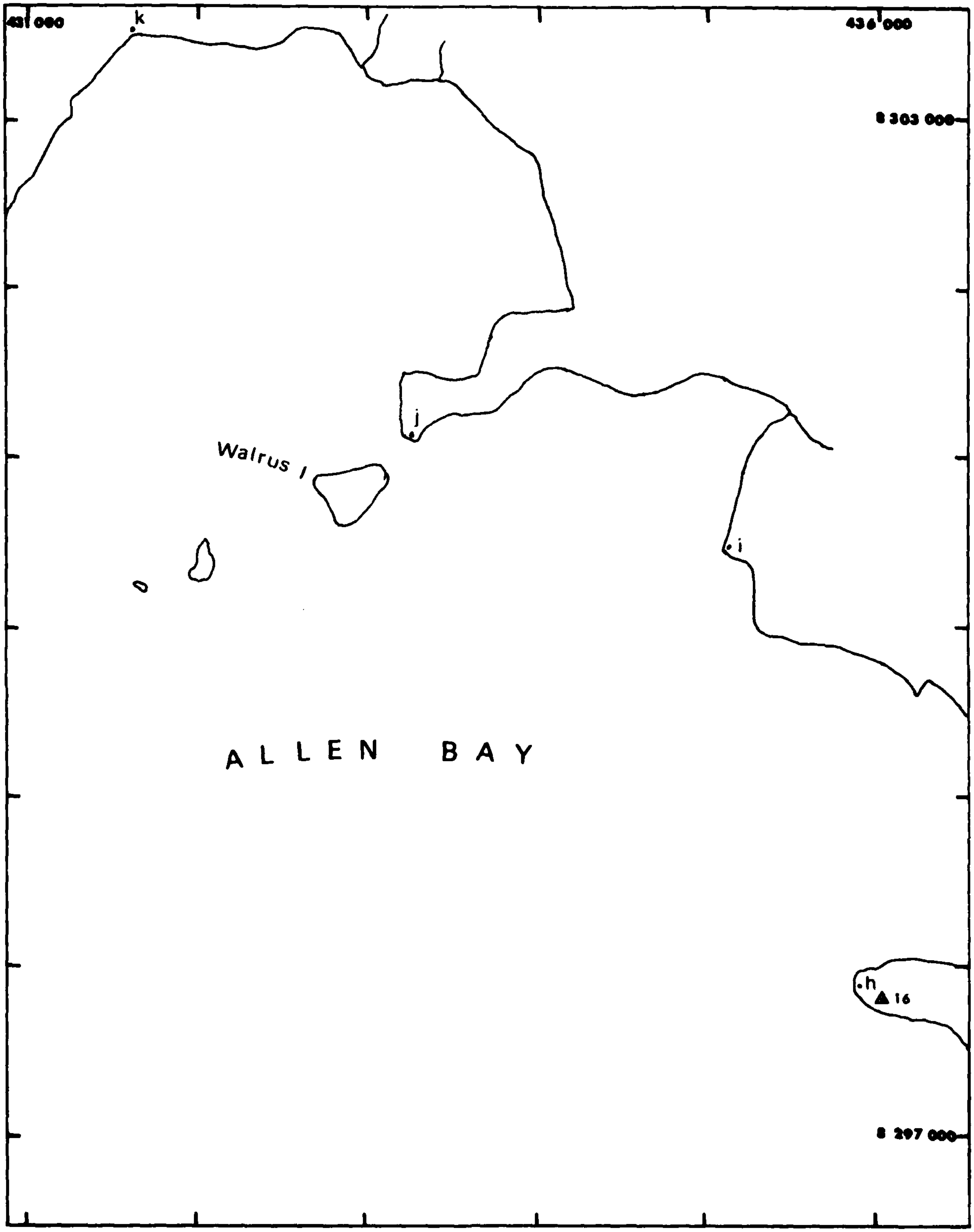


Figure 4. The eastern side of Allen Bay. Grid markings and spot heights are in metres.

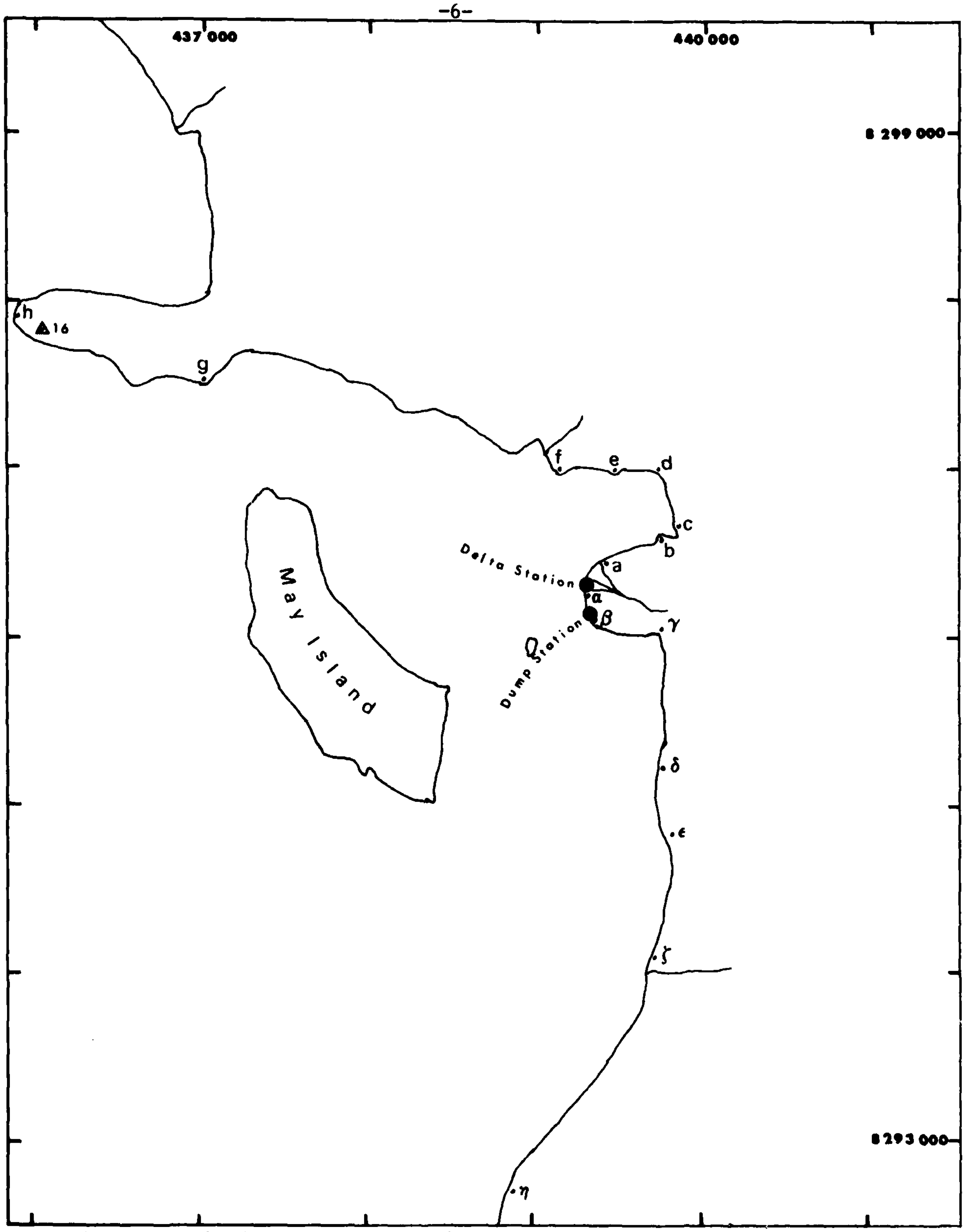


Figure 5. May Island area showing Delta and Dump Stations. The lower-case Roman and Greek letters indicate reference points used in the field diary. The streams shown are all seasonal, that at Delta Station being one of the two largest in the area. Grid markings and spot heights are in metres.

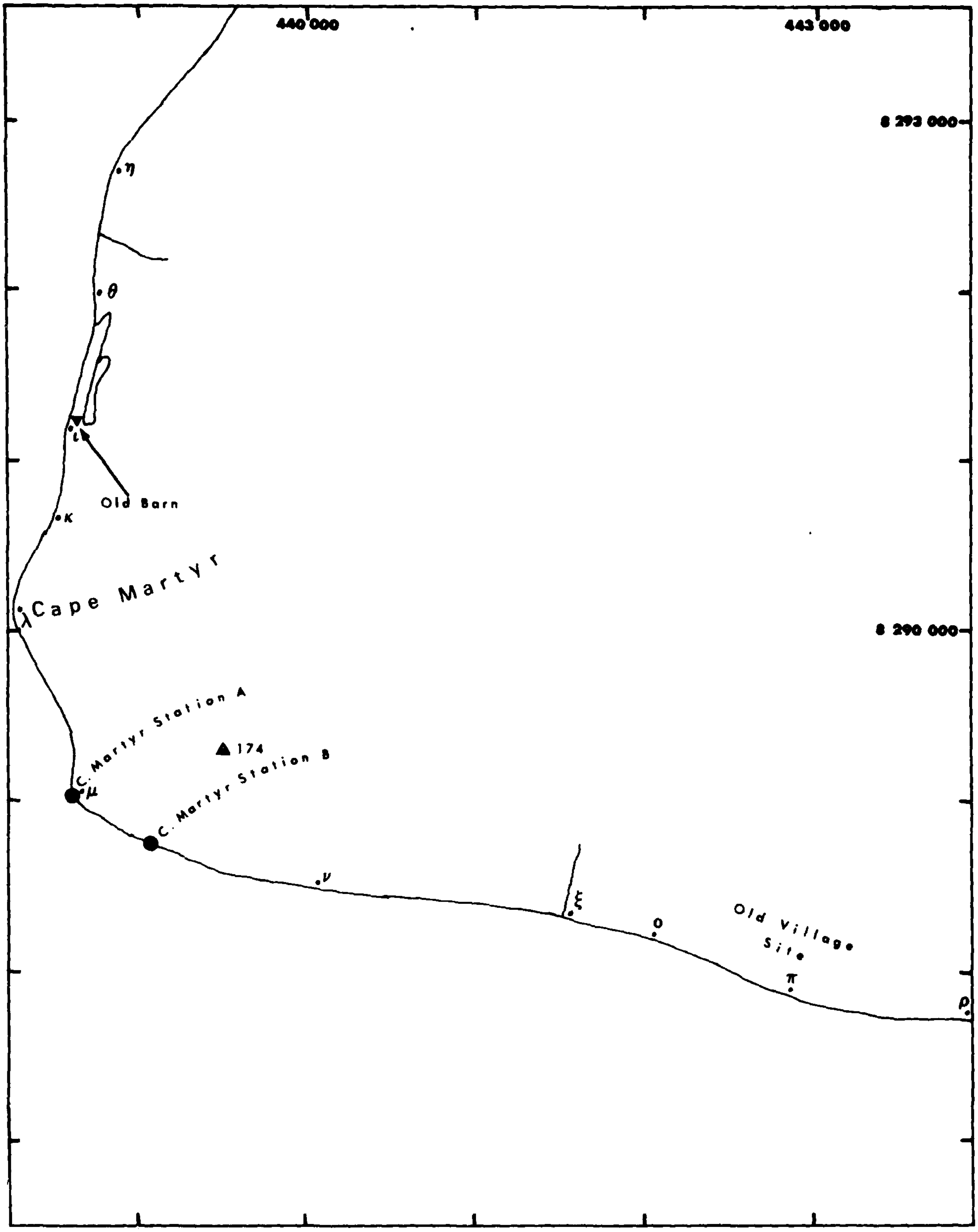


Figure 6. Cape Martyr area showing Cape Martyr Stations A and B. Grid markings and spot heights are in metres.

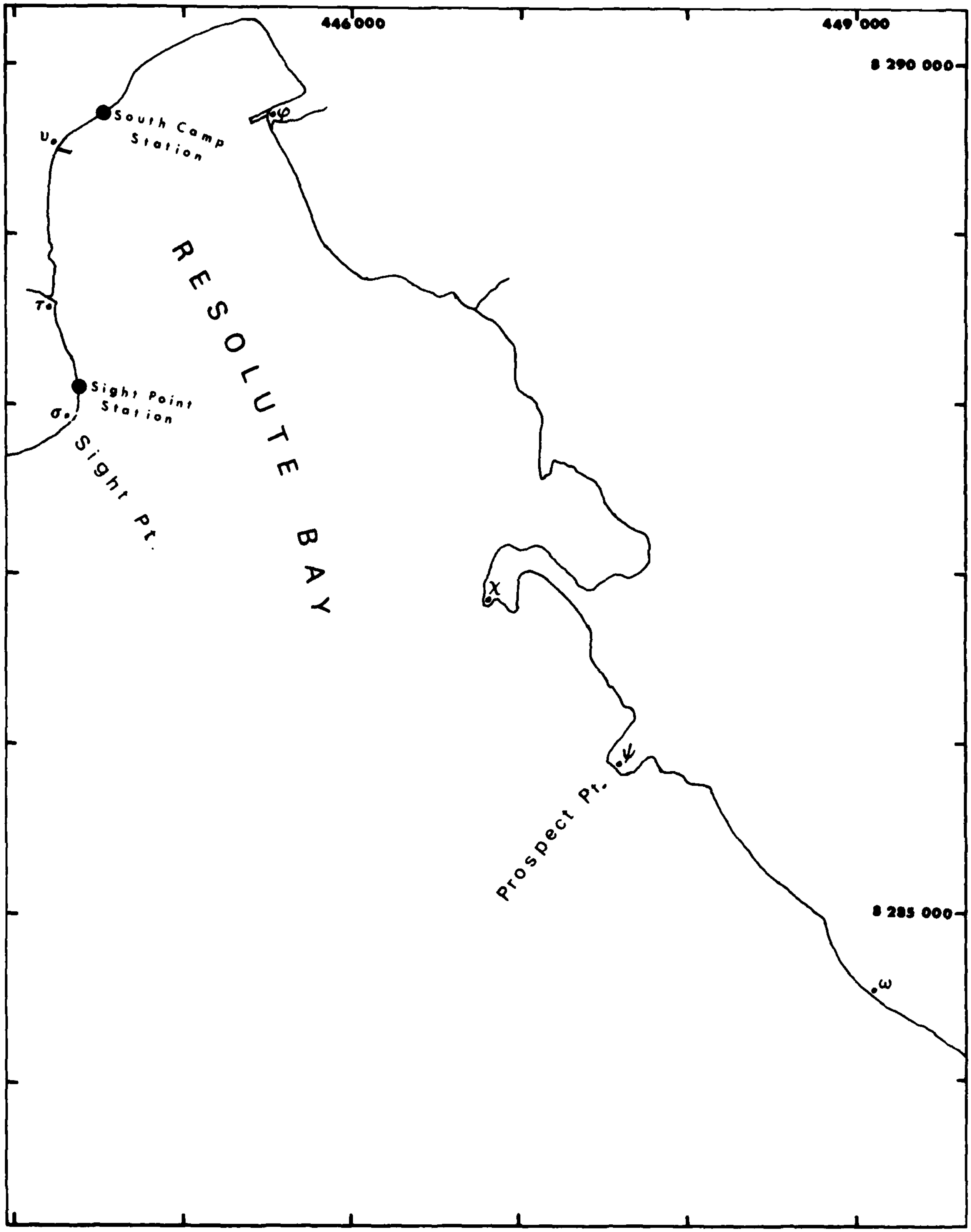


Figure 7. Resolute Bay showing Sight Point and South Camp Stations. Grid markings and spot heights are in metres.

floes and the likelihood of their being moved. At the Sight Point station we set up an experiment in the use of local materials (gravel from the beach berm) in accelerating the melting and break-up of ice in a bay.

We returned between 1 and 15 July 1978, arriving just as the delayed summer melt began. Almost all of the annual run-off took place in the next nine days, the rate of flow of fresh water onto and under the sea ice being much greater than normal. All the small rivers and creeks were running high and run-off water seeped through the gravel into the sea almost everywhere along the beach. At each of the 6 stations surveyed in May 1978, we established ablation stakes, obtained vertical temperature and salinity profiles in the ice and carried out crushing strength tests. We also plotted the positions of all visible cracks in the sea ice, investigated the structure of the grounded floes off the Sight Point station and made stereo-photographs of the icefoot and the sea ice.

Between 3 August and 26 August 1978 we laid arrays of light cable at three of the stations, shown in Figures 5, 6 and 7 as Delta, Cape Martyr B and Sight Point Stations. At each station 5 cables, each 150 m long, were placed in a fan shaped pattern with the inshore end of each cable being brought to a pit dug near the survey marker where individual timing devices and batteries were connected to the cables before burial. The cables ran in a shallow trench dug across the beach zone to about LLWS level, they then ran unprotected on the sea bed out to a light anchor. We completed these installations at only three stations because of the unusually delayed break-up of the sea ice in 1978. Over most of the length of the beaches in the area the shore lead was either non-existent or very narrow, and only in these 3 spots was there sufficient room to lay 150 m of cable off-shore with our small boat. The station at Cape Martyr which we had surveyed in May was completely blocked off by heavy grounded floes and floating brash ice, so that we were forced to move about 300 m east to Cape Martyr Station B (Figure 6). The ice at Delta Station did not move out sufficiently for us to lay cables until 19 August. Several other locations in the area were checked as possible last minute substitutes but none of them was satisfactory for one reason or another. When laying the cables we took samples of the beach gravel every 3 m and these were later analysed for size distribution. An echo-sounder was used in the boat to obtain depth profiles along the cable runs and we also completed the measurements of the ablation of the sea ice under the strip of gravel laid in May.

During the winter of 1978-79 two parties visited the sites. In November we obtained temperature and salinity profiles of the sea-ice at all stations and made a general reconnaissance of the whole beach. The second visit, made in February 1979, was largely unproductive because of the record low air temperatures, which remained between -45°C and -56.5°C for the whole 10 days, making travel outside the camp dangerous because of the likelihood of vehicle and equipment breakdown. We did obtain some measurements of ice thickness and temperature profiles in Resolute Bay and made a single reconnaissance along 10 km of beach front.

Returning on the 28 April 1979 we completed a resurvey of the 3 cable stations, levelling to the upper surface of the ice and obtaining readings for the ice thickness, freeboard and water depth. Temperature and salinity profiles were made and a plan of the distribution of cracks in the ice was completed. We also completed a running survey of the ice conditions for about 30 km along the beach from Cape Sheringham to Prospect Hills, and also for 10 km along the eastern shore of Griffith Island.

A short visit between 30 June and 7 July indicated that the breakup was likely to be even later than in 1978. On arrival there was no sign of melt water on the ice and no open cracks. A week of warm, sunny weather (-5°C to +5°C) produced melt pools covering about half the ice surface but there was still no sign of breakup movement at any of the stations. We obtained ablation measurements and temperature and salinity profiles and rechecked the pattern of ice cracks at each station, now more clearly visible.

The last field trip was made between 29 August and 7 September 1979. Although the ice had broken up, the vicinity of the stations and the off-shore area around the whole of the south west corner of Cornwallis Island was full of brash ice and small blocks. We recovered all of the timers and most of the cables at Sight Point and Delta Stations during the first three days. Early on 1 September, a wind gusting to 60 km/h from the SE piled up ice onto the shore all along the southern coast of Cornwallis Island, forming a wall of rubble at Cape Martyr B which was about 6 m high and which covered the beach to within 10 m of the timer pit. Here we recovered the timers, but only 10 m to 20 m of cable from each line. On 7 September a high wind from the NW cleared almost all of the ice from the shore area, except for that piled up on the beach, but sea conditions were too bad to use the small boat in any attempt to drag for the seaward end of the cables at Cape Martyr. A general survey of the shoreline over the whole area completed the operation.

OBSERVATIONS AND RESULTS

ICE CONDITIONS AT BEACH STATIONS

Since the aim of the investigation was to find simple criteria by which to choose instrument locations, a sampling of sites with differing beach geometry, bathymetry and exposure was necessary. From charts and photographs we selected a dozen possible sites for examination on the ground, but in the absence of previous bathymetric surveys over almost all of the coast line, a number of these stations proved to be too shallow and ice cluttered. We were further limited by the unusually delayed break-up in the summer of 1978 since we required a strip of open water off-shore to lay test cables.

The requirements for establishing a station were that

(i) it should be conveniently located so that people and equipment could be transported to the site from the base camp at Resolute Airport at any season of the year,

(ii) the shore line and off-shore area should be clear enough of grounded ice and erratic blocks to permit survey lines to be run using standard techniques out to at least 150 m from the shore,

(iii) the bathymetry should be such as to permit the outer ends of 150 m test cables to be anchored in water of sufficient depth to ensure that sea ice of normal thickness (2 m) should not ground onto the anchors at any state of the tide.

The positions examined and those selected are listed here, their locations being shown in Figures 3 to 7.

Sheringham Spit Station (Figure 3)

We selected this site as an example of a sheltered location protected from gross ice movements. It lies on the north west side of a narrow sedimentary rock outcrop about 600 m long and 50 m wide which blocks the southern half of the entrance to Sheringham Bay. The crest of the spit slopes from a height of about 10 m at the base to 3 m near the tip, enough of an obstacle to reduce the effects of southerly winds on the near-shore ice and to allow the formation of a comparatively deep (2 m) snow bank along the north western side. The only obvious sources of possible ice movement are the tidal rise and fall of the ice and the on-shore pressure due to the frictional effects of north easterly winds acting over a very limited fetch inside the bay itself.

We surveyed a line perpendicular to the beach in May 1978, travelling to the site over the sea ice, but unfortunately, in August 1978, we found that the overland route around the northern shores of Allen Bay (Figure 4) was very difficult, with many rock outcrops and loose boulders. The time required to travel to the site was about 6 hours each way, and the bad conditions would have damaged the vehicle being used for transport. Since this meant that we would be unable to visit the site at any time except between February and May, no test cables were laid there. One of us revisited the site in May 1979 and found the ice conditions near the beach to be very similar to those found in 1978.

"51 Foot Point" (Figure 5, Point h)

This point is also formed by a narrow projecting rock outcrop at the south eastern limit of Allen Bay. The bedding plane of the sedimentary rock is almost horizontal, the strata continuing under water around the point and producing very shallow water for some distance off shore. The whole area was littered with grounded ice of all sizes up to 3 m thick. We revisited the site in August 1978 since the coast line between Points g and h was then one of the few stretches of beach where the ice had moved off-shore, but an examination from the boat using lead line and glass-bottomed bucket still failed to find any line suitable for test cables.

"North Cove" Site (Figure 5, Point c)

This site, lying at the head of a small bay north of a river delta, is open to the west while still being partly protected from massive ice movements by May Island. In May 1978, however, we found that the sea ice was grounded as far as 200 m off-shore with a large number of scattered blocks mixed up in it. In August 1978 the shore lead, apparently formed by fresh-water runoff from the delta, remained less than 10 m wide and test cables could not be laid.

Delta Station (Figure 5)

The position of Delta Station was established about 50 m north of the southern extremity of the delta formed at the mouth of the seasonal stream which runs in a ravine north of the airstrip and radio station. The river drains an area of about 25 km^2, the run-off coming mostly in two or three weeks. In 1978, an exceptional year in this regard, the greater part of the run-off came in a period of 8 or 9 days at the beginning of July, but even at this unusual level the southern distributaries remained dry. The station marker was set up on the beach berm which was about 2 m wide and 0.5 m high above the level of HHWS. The area behind the berm is flat and is flooded only at spring tides once or twice a year. The shore line is convex at this point, but like the "North Cove" site it is protected by May Island from massive ice pressure from Resolute Passage. We surveyed the ice profiles in May 1978, and again in May 1979. In August 1978 the shore lead opened just wide enough for us to lay test cables and carry out a bathymetric survey from a small boat. Access was comparatively easy all year round and measurements were made on the sea ice in November 1978 and in February, May, July and August-September 1979, the timing instruments and cables being retrieved on 31 August 1979.

Dump Station (Figure 5)

This site lay about 200 m south of Delta Station, on a convex shore line which was more exposed than that at Delta Station while still being protected by a small islet and a reef lying between May and Cornwallis Islands. We completed the initial surveys in May and June of 1978 but in August of that year the sea ice did not move off the beach more than about 20 m during the whole time and no test cables could be laid.

"South Cove" Site (Figure 5, point γ)

Lying about 400 m east of Dump Station, this site is in the corner of an indentation open to the south west. In May 1978 grounded ice stretched for 200 m or more off-shore and the tide crack region was highly distorted. Most of the grounded ice was still there in August of 1978 and the shore lead did not open up at all. It is worth noting that in May 1979 this area was clear of grounded ice. The tide cracks were regular in formation, and, if the same conditions had held in May 1978, the site would have been considered ideal for laying cable.

Old Barn Site (Figure 6, Point ι)

The shore line here is generally straight, consisting of a gravel berm exposed to pressure from Resolute Passage from westerly winds. In both 1978 and 1979 there was a great deal of heavy grounded ice for 300 m offshore, including multi-year floes up to 4 m thick. The site was so obviously unfavourable that no detailed surveys were undertaken here.

Cape Martyr Station 'A' (Figure 6)

We chose this station as an example of a highly exposed, rapidly shelving, convex shore-line. Forming the south western extremity of Cornwallis Island, the beach falls away with a gradient of about 1:10 for 20 m and then drops off at 1:3. Behind the HW mark the beach gravel slopes rapidly up into the hillside which reaches 160 m within 200 m of the shore. It is exposed to direct wind and wave action from the whole southwestern semicircle, and to the translational movement of the ice carried by the tides in Resolute Passage. In May 1978 several floes of 4 m thickness were lying on the beach at the HW mark but a line was surveyed out between them at right angles to the axis of Resolute Passage. The snow bank on the upper part of the beach was over 4 m thick at one point, and we had to establish intermediate survey marks. In August 1978 the ice conditions were even worse; there were more grounded floes, with floating ice tangled up in them, so that it was impossible to lay test cables at this station and we were compelled to move to another site.

Cape Martyr Station 'B' (Figure 6)

This station lies about 300 m east of the last one on a straight stretch of gravel beach with the land rising sharply behind it. The sea bed falls away fairly rapidly although not quite so fast as at Station 'A'. The beach at this point was completely clear of ice, and this enabled us to lay test cables and complete a bathymetric survey. We made further observations in the subsequent November, February, May and August, and recovered the timers and cables in September 1979 when the beach was lined by a wall of ice rubble more than 6 m high.

Old Village Site (Figure 6, Point π)

A straight gravel beach with a pronounced berm (1 to 2 m high) runs for two kilometres between points o and ρ , the sea bed shelving gently off-shore. In May 1978 ice lay grounded in a belt 100 to 300 m wide, most of this ice being still there in August. No survey was feasible. In 1979 there was much less grounded ice, but the sea is so shallow that working tide cracks were found as much as 250 m from the shore line. On 1 September 1979 the whole beach was lined by rubble driven ashore by high winds.

Sight Point Station (Figure 7)

We chose this site as an example of a convex shoreline protected from the full pressure of ice in Barrow Strait by the shallow water to the south. The bathymetric survey completed in August 1978 showed that in fact the whole area of the station lay in shallow water, the reason for the uncluttered condition of the beach and tide crack area being the protection afforded by heavy floes grounded about 100 m off-shore to the east and south east of the station marker. The open water at this time extended only out as far as these floes so that some of the test cables were not laid to their full length. The beach between points ρ and τ consists of a gravel berm 1 to 1.5 m high and 10 m wide with lagoon-like areas behind at about the level of HHWS. These lagoons are flooded by run off and stagnant water remains in some of them all year round. The land behind these swampy areas rises to about 15 m above sea level.

South Camp Station (Figure 7)

This station lies on a straight gravel beach at the head of Resolute Bay. The beach berm in 1978 was low - less than 0.5 m - and there was little evidence of ice push onto the beach. In May 1978 when the centre line was first surveyed there was a little grounded ice on either side of the centreline at the tide cracks and one large grounded floe about 200 m south east of the marker. A long core (10 m) was taken from this floe to check structure. In August 1978 the shore lead never developed at this station and we could not lay test cables.

Prospect Point Site (Figure 7, Point ψ)

This site provides an example of an area exposed to ice pressure from the south, but we were unable to use it. The point is formed by a low sedimentary rock formation, with nearly horizontal bedding planes, which extends underwater for several hundred metres around the point. The water is very shallow over this whole area, usually less than 1 m in depth, and grounded ice surrounded the point out to 100 m making it impossible to find any line on which to lay test cables.

Prospect Hills Site (Figure 7, Point ω)

This site is similar in exposure to that at Cape Martyr but with extended shallow water off-shore. In both 1978 and 1979 large blocks of ice lay grounded out as far as 0.5 km from shore and active tide cracks lay as much as 300 m from the beach. No survey was done at this station.

ICE PROFILES AT BEACH STATIONS

We surveyed six stations in May 1978, and repeated two of the surveys in May 1979 together with one at an additional station. At each place we established a survey marker on the beach berm or behind it and then cut a trench about one metre wide at right angles to the beach. We removed the snow down to the beach gravel or the ice and recorded the level of the ice surface at about 20 points along the trench, out to a point well beyond the last working tide crack. At each survey point we recorded the ice thickness, the water depth, the freeboard of the ice and the depth of the snow cover. We sketched the ice surface between survey points using tape measure distances and heights, and we noted the positions of all cracks. At the end of each line we carried out current measurements, obtaining current profiles every metre down to 10 m. We measured the temperature and salinity profiles of the ice and carried out compressive strength measurements, snow density measurements and current readings.

The ice surface was surveyed at both high and low water and the predicted tides at Resolute Bay were used to correct the profiles to HHWS and LLWS. A tide pole, established at Delta Station to check time and range differences between this station and the tides at the reference point in Resolute Bay, showed only small discrepancies. The time lag was less than 10 minutes - about the same as the uncertainty of the tide pole readings - while the range was within 0.05 m of that in Resolute Bay. We therefore assume that the predicted tides at Resolute Bay represent the tides at the other two stations within the accuracy of the survey measurements. The corrected water levels obtained from the measured freeboard of floating ice and that obtained by direct levelling to the surface agree within ±3 cm, and we consider that the sea ice surface profiles and the snow surface profiles are accurate to ±5 cm in height and ±20 cm in distance after adjustment to HHWS and LLWS. The ice bottom profiles and the sea bed profiles, drawn from spot readings several metres apart, do not have the same accuracy except at the points where a change in gradient is indicated. The profiles obtained in both years are shown in Figures 8 to 22, Figures 8 to 19 showing profiles corrected to HHWS and LLWS at the 6 stations surveyed in 1978 and Figures 20 to 22 the profiles in May 1979, corrected to LLWS, at the 3 stations where the test cables were laid.

It will be seen that only at Dump Station (Figures 12 and 13) did the profile give any indication of relative vertical slipping at the tide cracks. In that case the ice outside the crack at 29 m apparently slipped vertically about 0.3 m but in general the ice tended to move up and down with the tides in the manner of a hinged plate rather than as independent pieces. This indicates that in May the fixed ice tends to keep the ice on opposite sides of the tide cracks pressed together to the extent that the friction and surface irregularities are sufficient to prevent individual zones of ice in the tide crack region from moving vertically to a condition of hydrostatic equilibrium. This is borne out by the flooded strip which appeared in most locations, the sea ice being depressed below the water level. The cracks as drawn are not intended to be accurate representations of the form of the crack through the thickness of the ice. The location at the surface and the width of the crack there are adequately represented, but the cracks are not rectilinear or of equal width through the whole thickness of the ice as is shown here since the ice on either side of the cracks is keyed together at some point below the surface.

The variation between different stations of the width of the zone in which the ice grounds at some state of the tide is obvious in these profiles. The data in Table 1, taken from the profiles, gives estimates of the width of this zone, a zone in which at some time an unprotected cable laid on the sea bed would be brought in contact with the ice cover at the time of its maximum thickness. The width is small at Delta Station and Cape Martyr 'A' Station, a few metres at Dump Station and Cape Martyr 'B' and relatively large at the other stations.

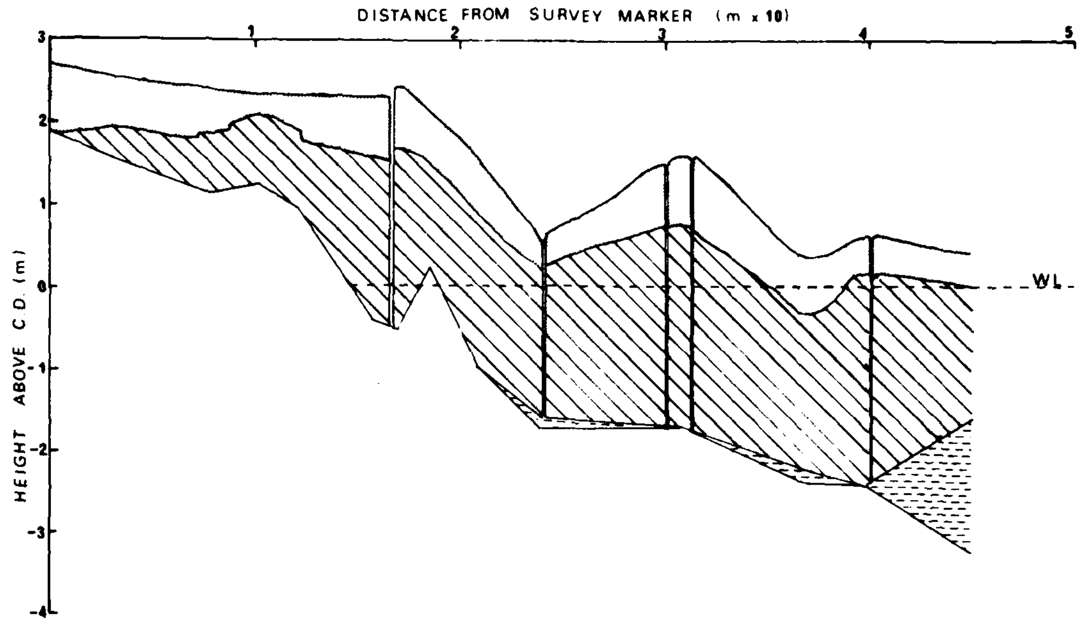


Figure 8. Profiles of snow and ice surfaces at Spit Station, May 1978, corrected to LLWS.

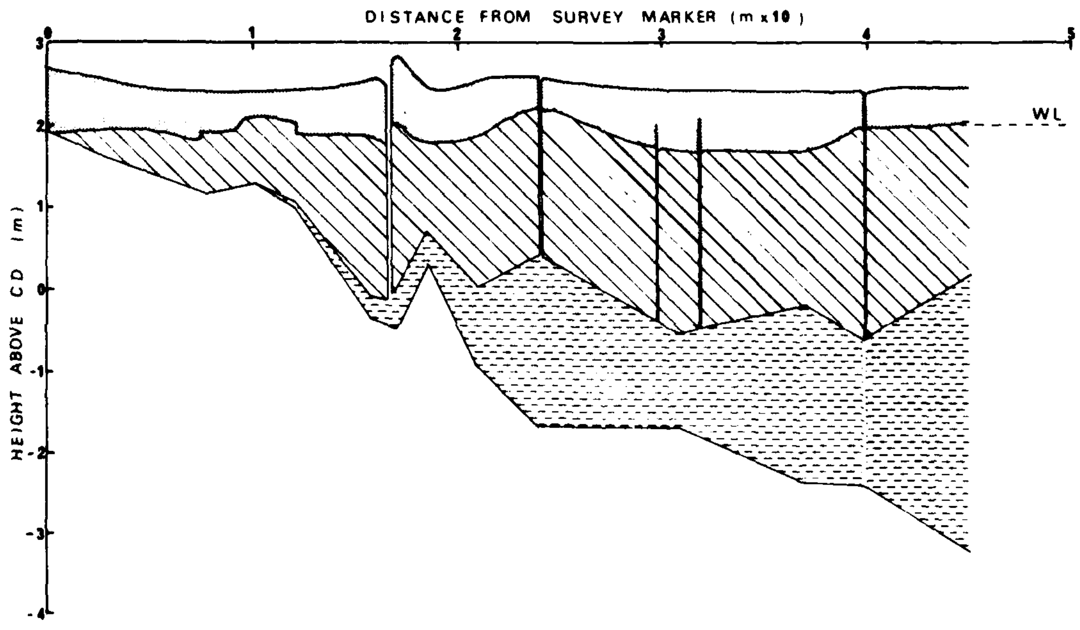


Figure 9. Profiles of snow and ice surfaces at Spit Station, May 1978, corrected to HHWS.

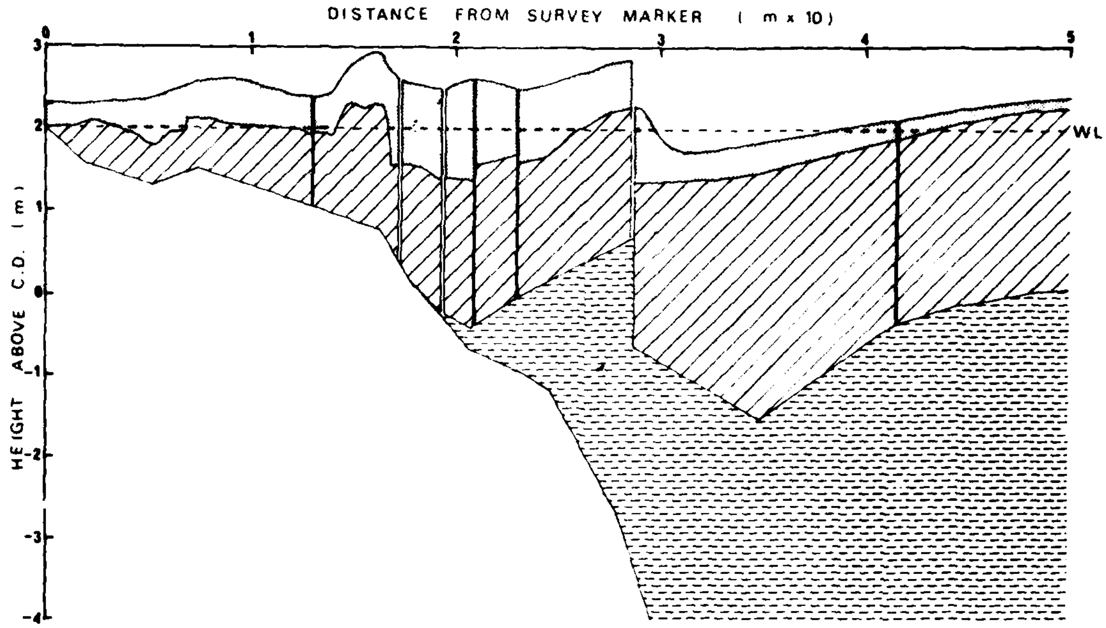


Figure 10. Profiles of snow and ice surfaces at Delta Station, May 1978, corrected to LLWS.

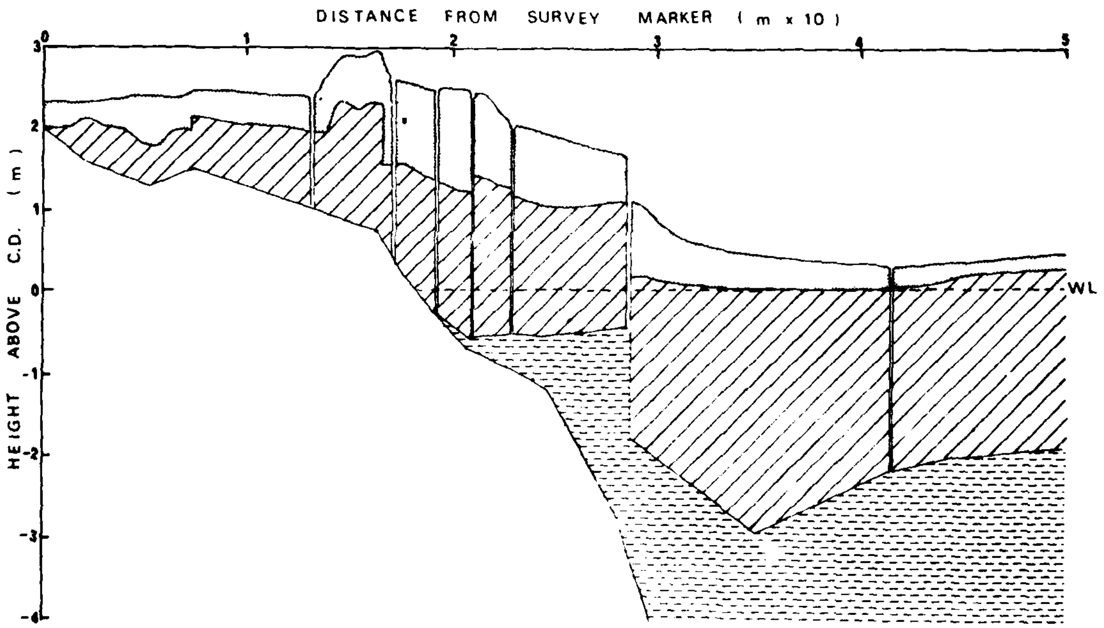


Figure 11. Profiles of snow and ice surfaces at Delta Station, May 1978, corrected to HHWS. Note the small vertical displacement at the 29 m crack, the only example of this kind of movement found.

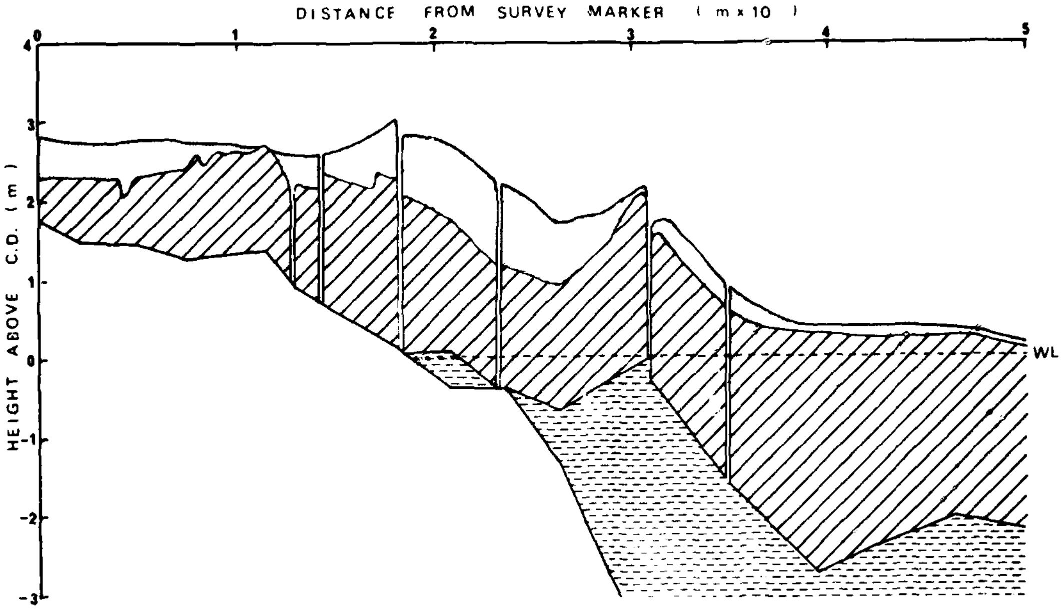


Figure 12. Profiles of snow and ice surfaces at Dump Station, May 1978, corrected to LLWS.

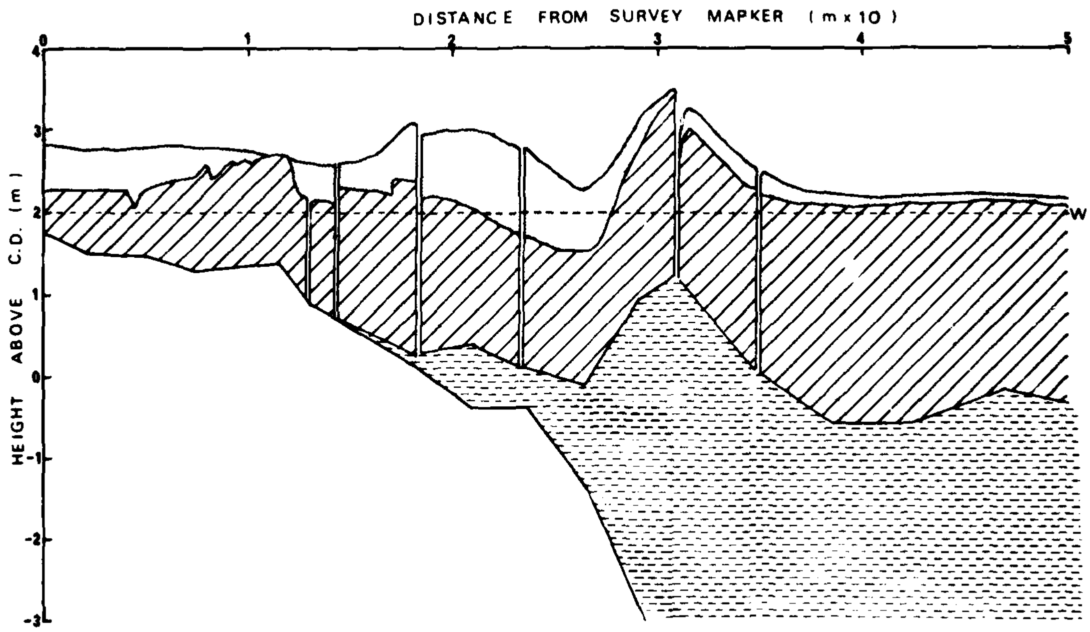


Figure 13. Profiles of snow and ice surfaces at Dump Station, May 1978, corrected to HHWS.

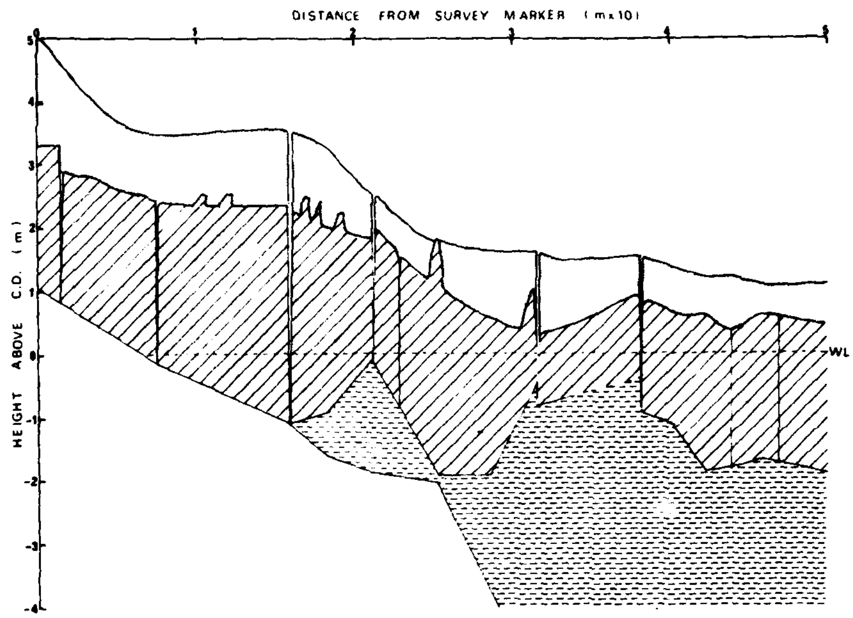


Figure 14. Profiles of snow and ice surfaces at Cape Martyr Station A, May 1978, corrected to LLWS.

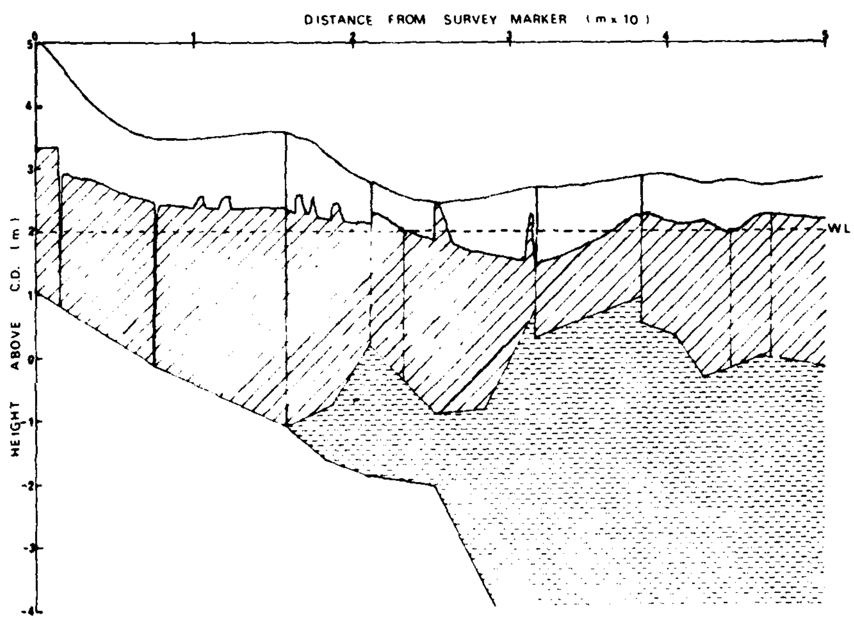


Figure 15. Profiles of snow and ice surfaces at Cape Martyr Station A, May 1978, corrected to HHWS.

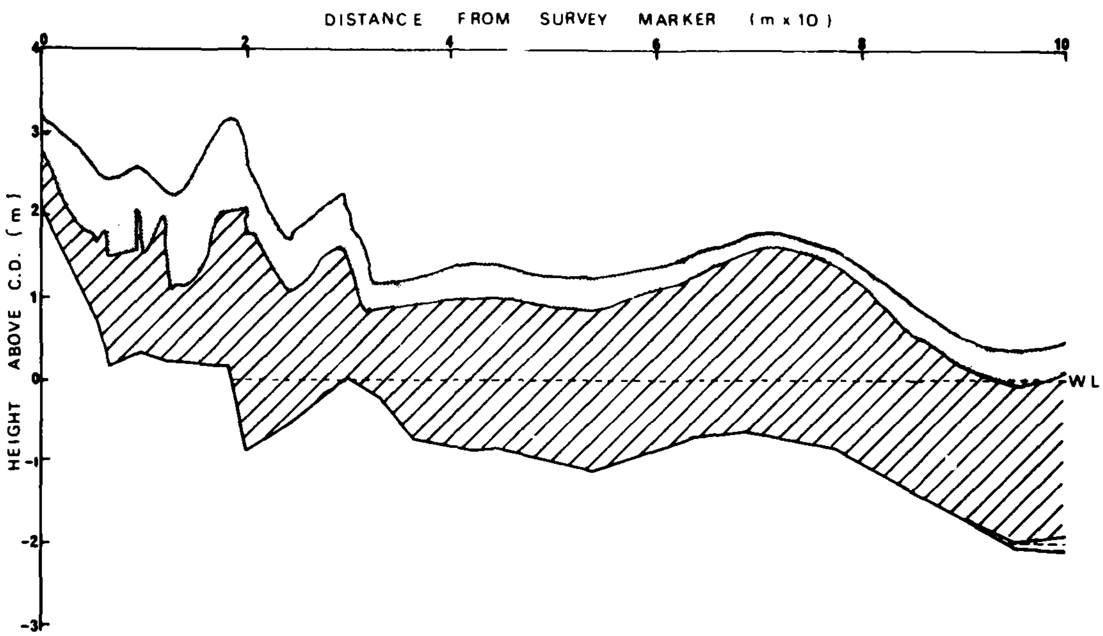


Figure 16. Profiles of snow and ice surfaces at Sight Point Station, May 1978, corrected to LLWS.

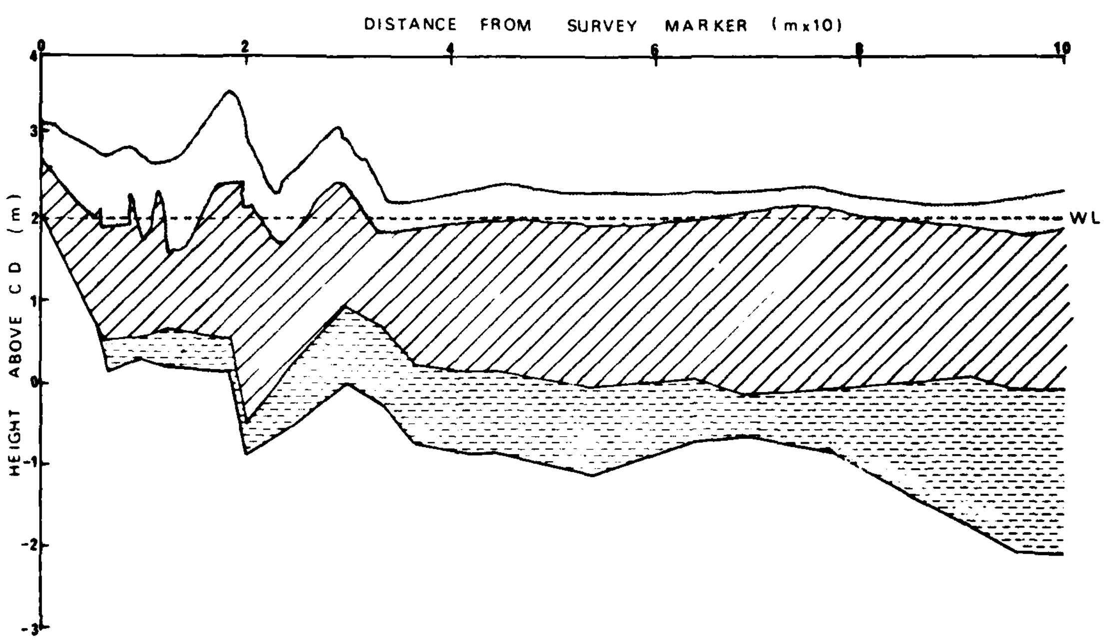


Figure 17. Profiles of snow and ice surfaces at Sight Point Station, May 1978, corrected to HHWS.

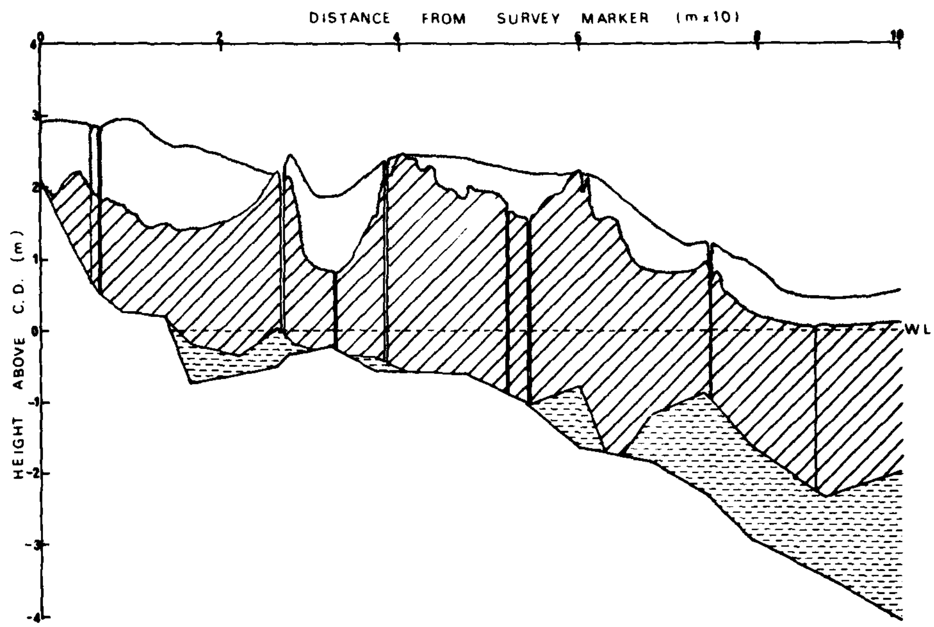


Figure 18. Profiles of snow and ice surfaces at South Camp Station, May 1978, corrected to LLWS.

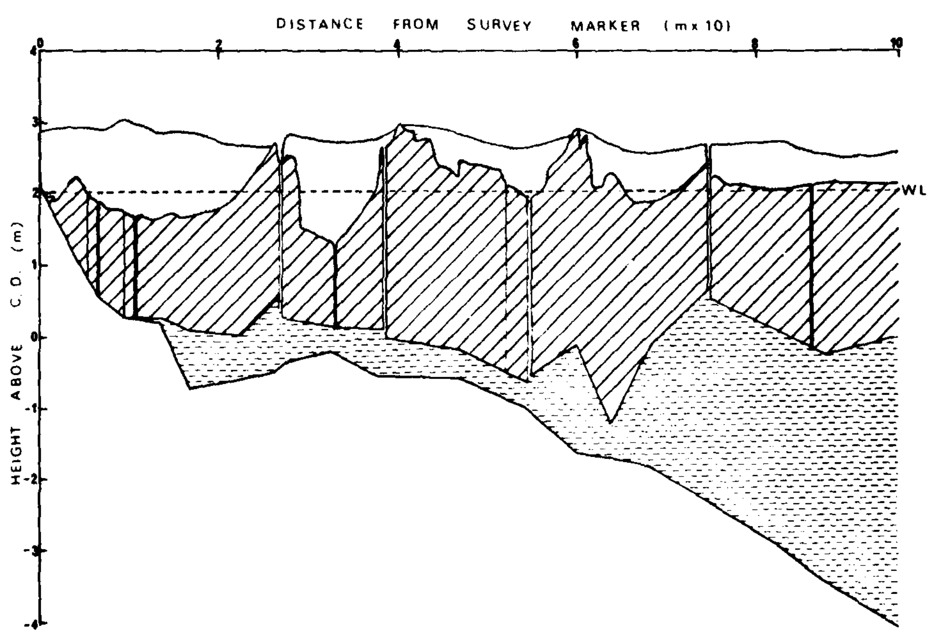


Figure 19. Profiles of snow and ice surfaces at South Camp Station, May 1978, corrected to HHWS.

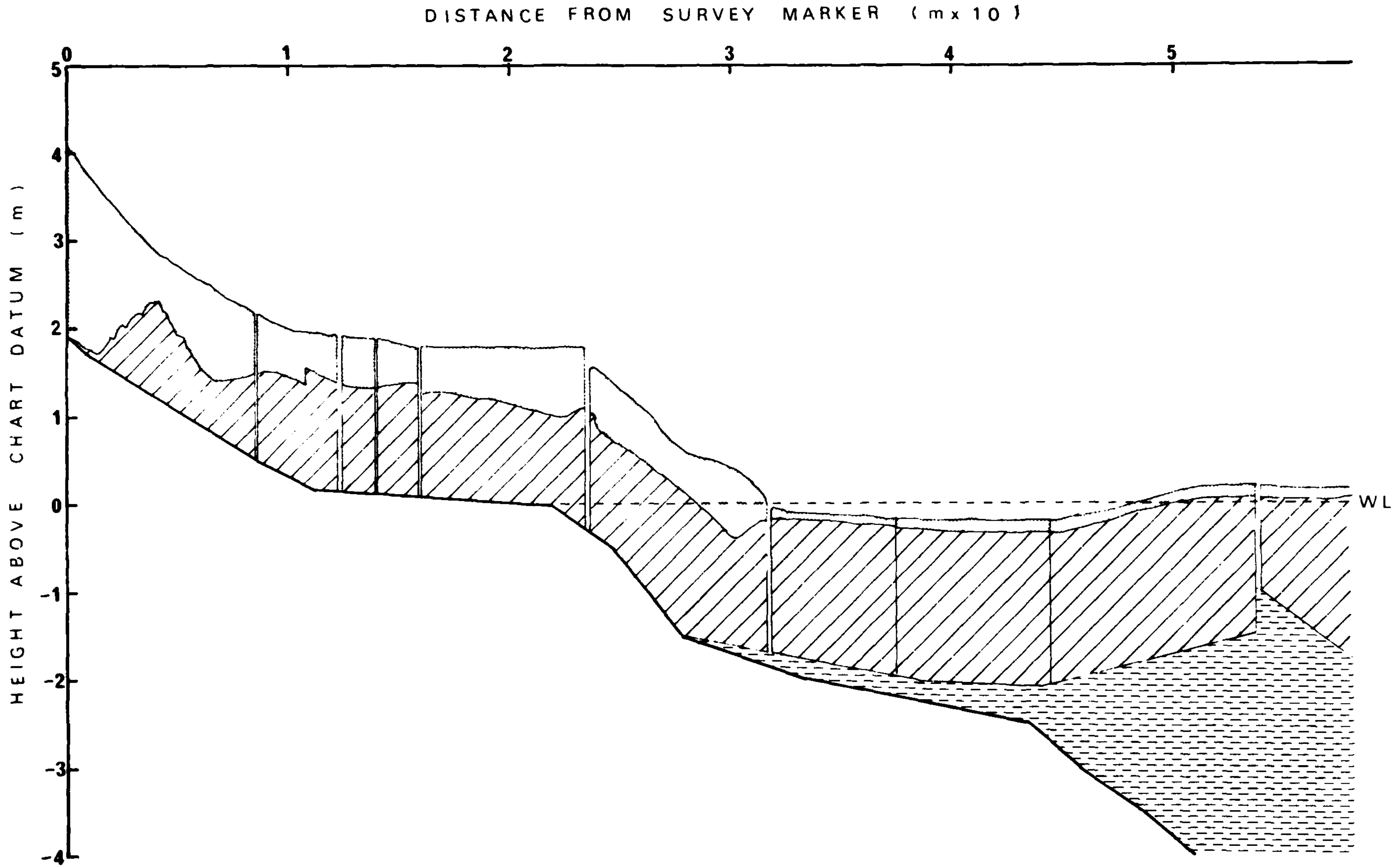


Figure 20. Profiles of snow and ice surfaces at Delta Station, May 1979, corrected to LLWS.

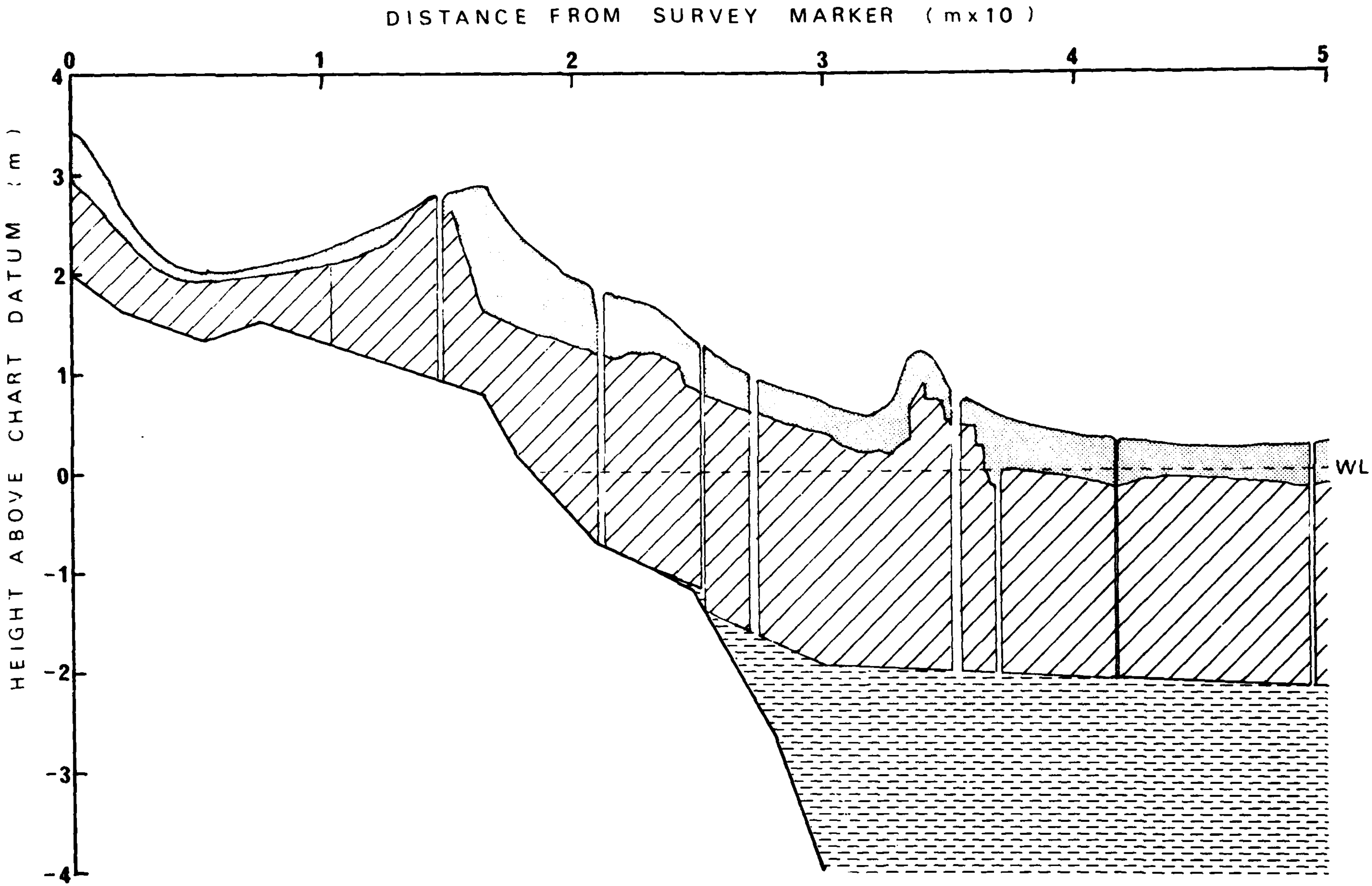


Figure 21. Profiles of snow and ice surfaces at Cape Martyr Station B, May 1979, corrected to LLWS.

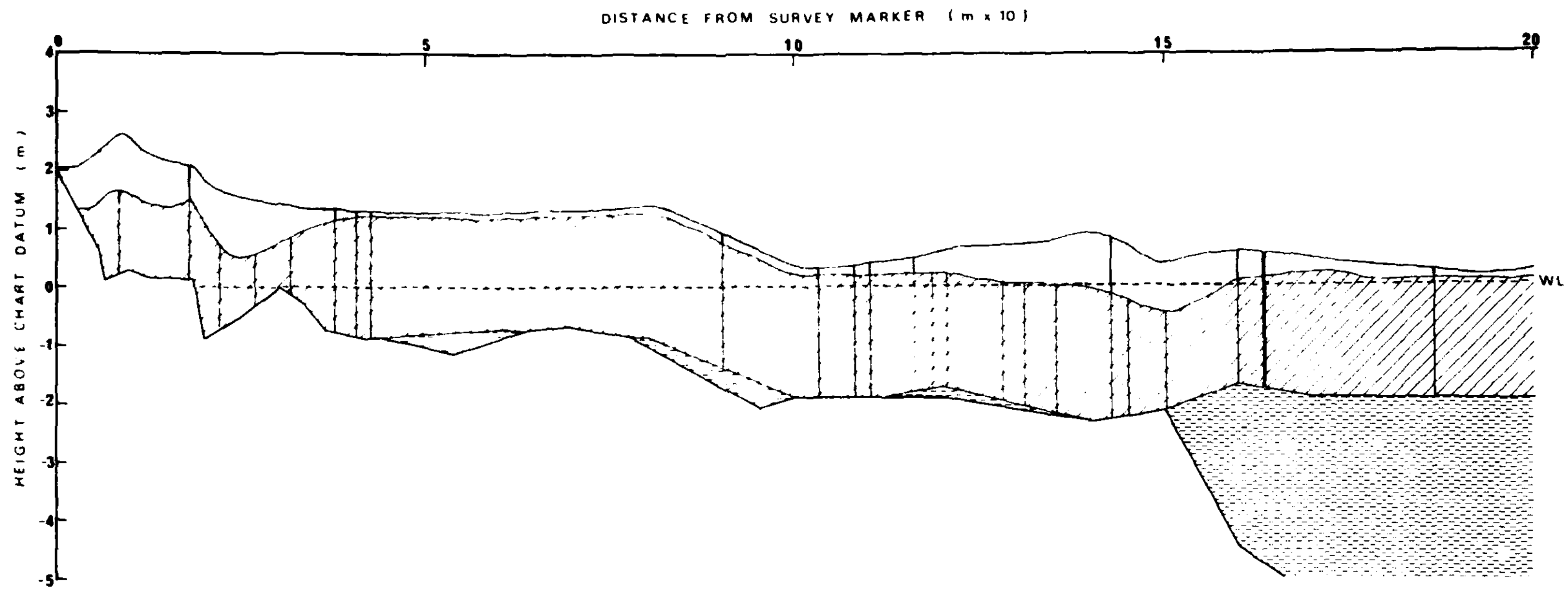


Figure 22. Profiles of snow and ice surfaces at Sight Point Station, May 1979, corrected to LLWS.

TABLE 1

WIDTH IN METRES OF ZONES IN WHICH THE SEA ICE COVER GROUNDS DUE TO VERTICAL TIDAL MOVEMENT

STATION	1978		1979	
	ZONE A	ZONE B	ZONE A	ZONE B
SHERINGHAM SPIT	10	30	-	-
DELTA	18	1	18	7
DUMP	13	10	-	-
CAPE MARTYR 'A'	16	0	-	-
CAPE MARTYR 'B'	-	-	20	13
SIGHT POINT	4	>88	5	145
SOUTH CAMP	10	54	-	-

Zone A. Ice grounded at all states of the tide.

Zone B. Ice grounded at LLWS but afloat at HHWS.

The profiles measured in 1978 and 1979 at both Delta and Sight Point Stations are very similar, as might be expected if the form of the ice foot and tide crack zone is determined by a constant bottom topography. Although we did not obtain profiles in both years at any of the other stations, it was obvious that this similarity between years did not apply to all of the beaches in the area. We have already mentioned the differences between years at Point γ (Figure 5) and similar remarks apply to most of the shore line between Dump Station and Cape Martyr 'B'. The pile-up of ice along the shore between Cape Martyr and Sight Point on 1 September 1979 made the ice conditions observed during a brief visit in March 1980 completely different to those observed in either of the two previous years. We are not justified in assuming that because a particular location was ideal for laying cables in any one year, the same conditions can be expected in most years.

PATTERNS OF TIDE CRACKS

In July 1978 we measured the location of cracks in the ice at each station along the centre survey line, Line C, to complete the description made in May. As the surface snow melts, the pattern of the cracks becomes clearer and the identification of actual working cracks more certain. When the ice first begins to form in early winter, the zone of contact with the sea bed is nearer to the shore line because of the relative thinness of the ice, and the working cracks are comparatively near to the beach. As the ice becomes thicker, the ice near the shore becomes so heavy that it does not lift with the rising tide, and the initial cracks cease to open, fill with snow, flood at high tide and become resealed, while at the same time other cracks open further out. The result is a general migration of the working tide cracks outwards from the shore until the ice reaches its maximum thickness in April or May.

The final pattern of tide cracks, old and new, may thus become very complex, particularly at a station where the water is shallow for some distance off-shore. In May 1979 we measured the position of the cracks over the full fan-shaped area covered by the test cables, and combined this with observations taken later in the summer as the snow disappeared from the surface to produce a plan of the cracks at Delta, Cape Martyr 'B' and Sight Point Stations. These are shown in Figures 23 to 25.

In Figures 26 to 28 a plan of the bathymetry at each station is shown. These were obtained by direct lead line soundings through the ice in May 1978 and 1979 and from the echo sounder records obtained in August 1978. All soundings were corrected to chart datum at LLWS Resolute Bay and are considered accurate to ±0.3 m along the five cable lines. Delta Station shows a fairly rapid, uniform slope from chart datum down to 10 m at a distance of 40 m off-shore with a deeper trough about 100 m out(Figure 26). The crack pattern at this station, shown in Figure 23, is generally regular

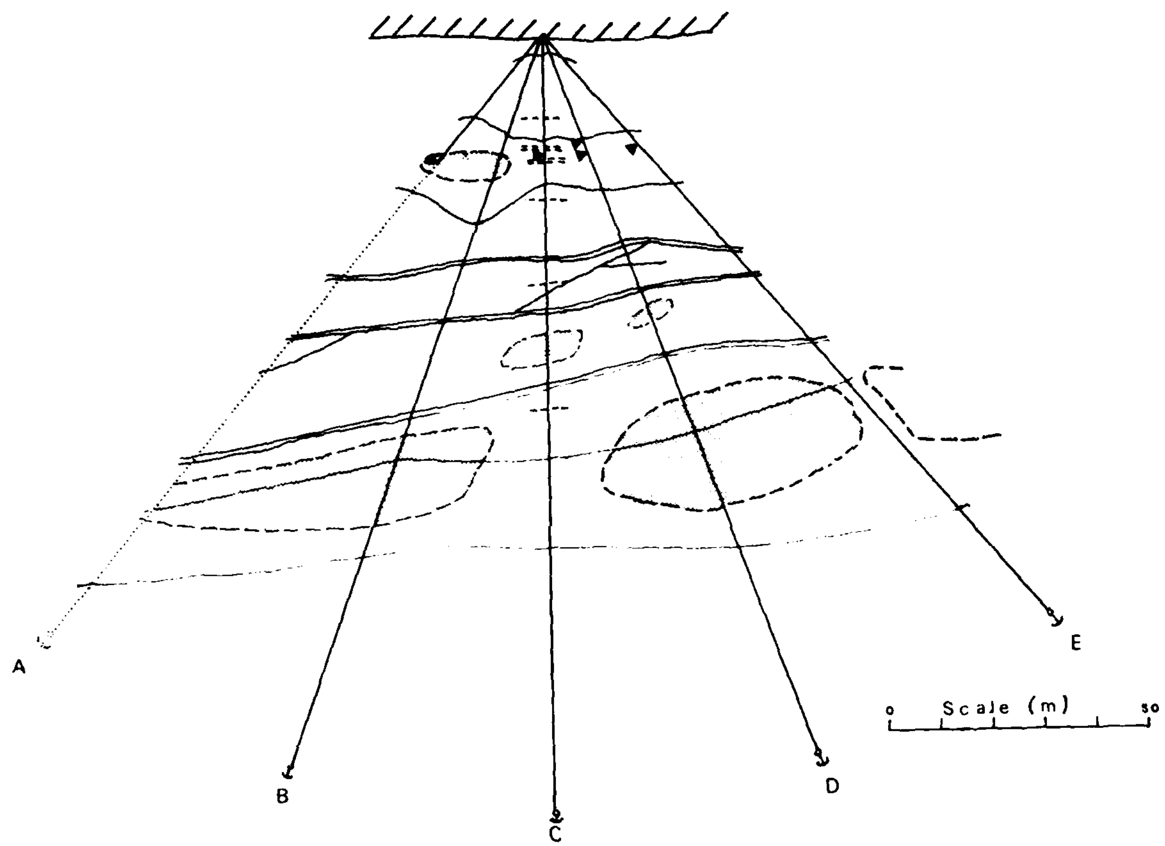


Figure 23. Plan of the positions of the cracks in the ice cover at Delta Station in 1979 (solid lines). The positions of cracks in 1978 are shown as short dashed lines crossing line C. The shaded areas were flooded at some state of the tide. The solid lines A to E indicate the cables and anchors actually recovered in August 1979 while the dotted portions show equipment not recovered. The solid triangles indicate the points at which breaks in the cable were found.

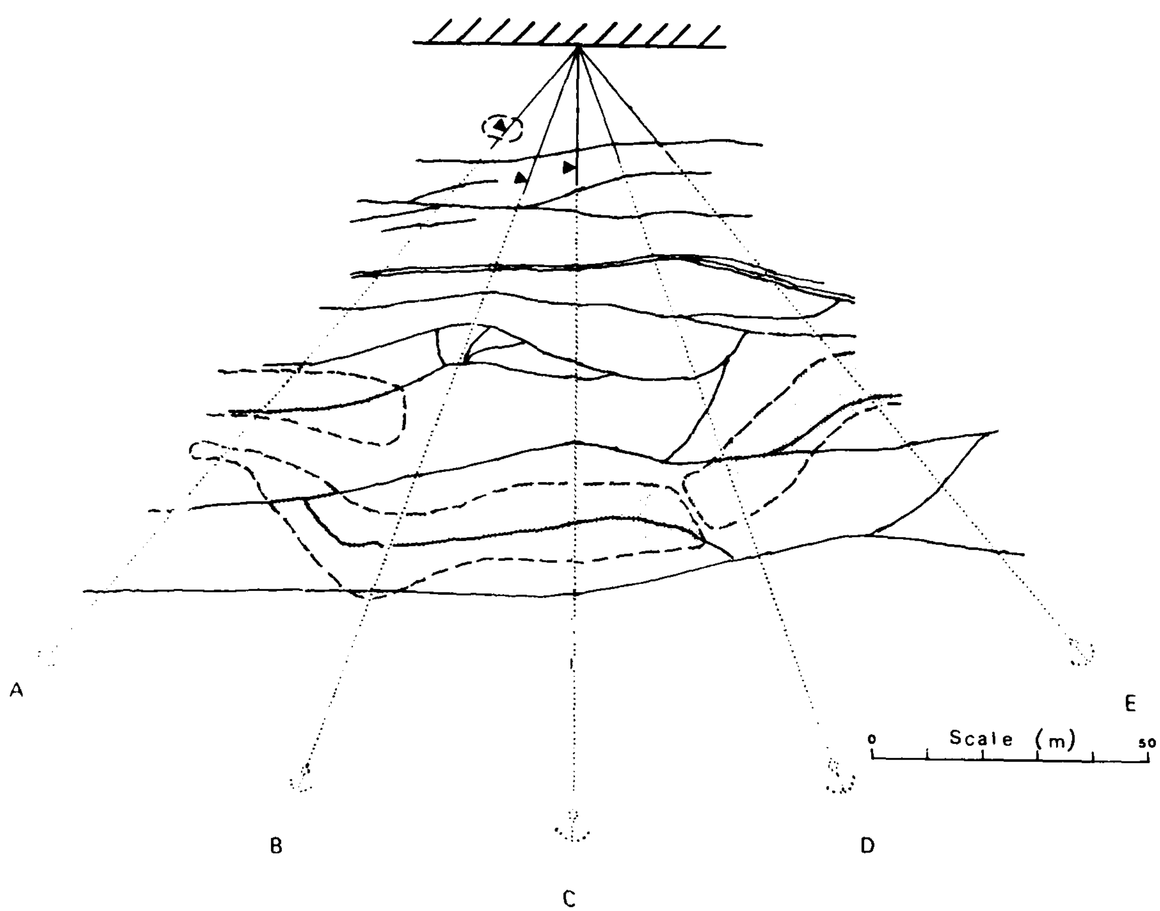


Figure 24. Plan of the locations of cracks in the ice cover at Cape Martyr Station B in 1979, shown as solid lines. The shaded areas were flooded at some state of the tide. The solid portions of lines A to E indicate the cables and anchors actually recovered in August 1979 and the dotted portions show equipment not recovered. The solid triangles indicate the points at which breaks in the cable were found.

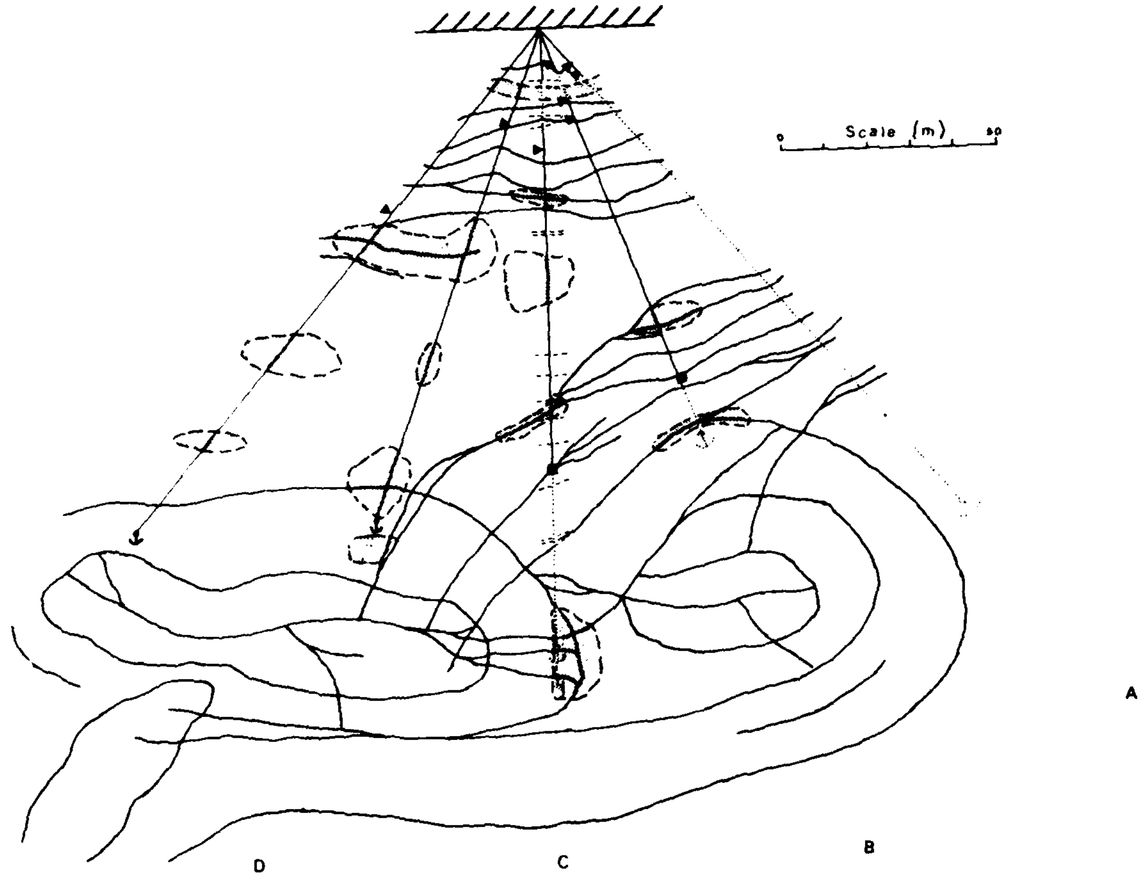


Figure 25. Plan of the locations of the cracks in the ice cover at Sight Point Station in 1979, shown as solid lines. The positions of the cracks found in 1978 are indicated by the short dashed lines crossing Line C. The shaded areas were flooded at some state of the tide. The solid sections of lines A to E indicate the cables and anchors actually lifted in August 1979, while the dotted portions show equipment which could not be recovered. The solid triangles indicate the points at which breaks in the cable were found and the solid squares the points at which the cable was intentionally cut as the ends ran under heavy grounded ice.

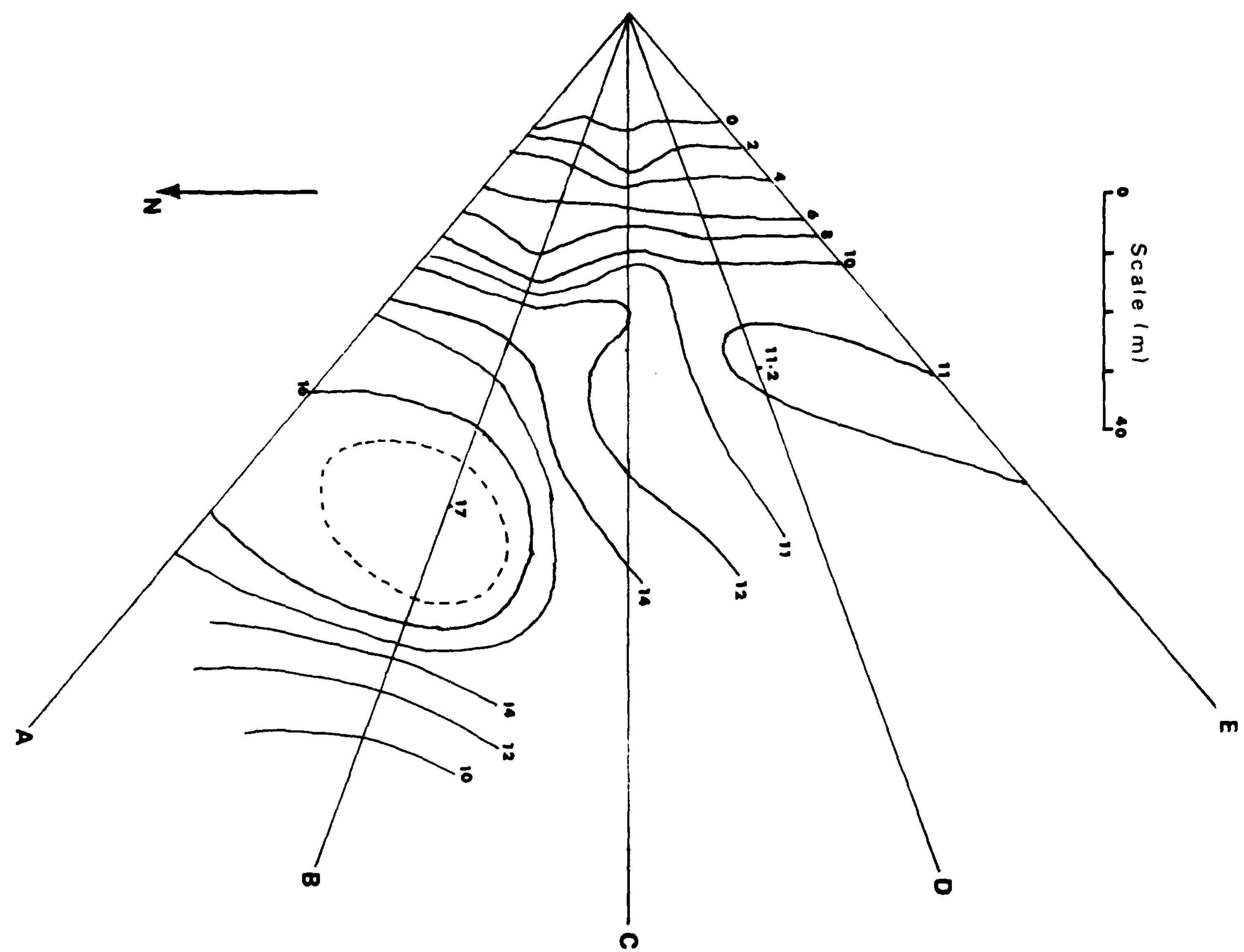


Figure 26. The bathymetry at Delta Station. The depths are in metres below chart datum at the level of LLWS.

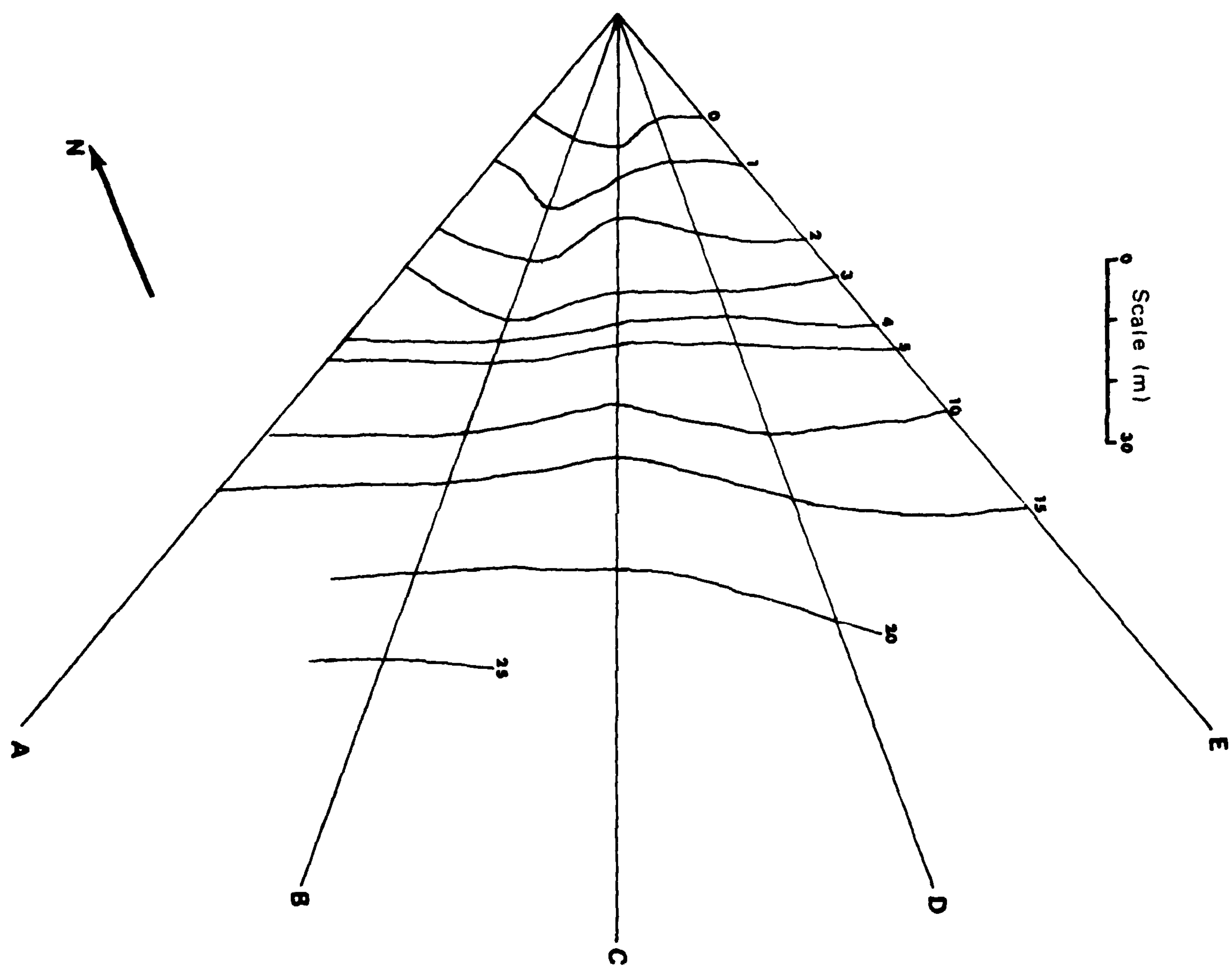


Figure 27. The bathymetry at Cape Martyr Station B. The depths are in metres below chart datum at the level of LLWS.

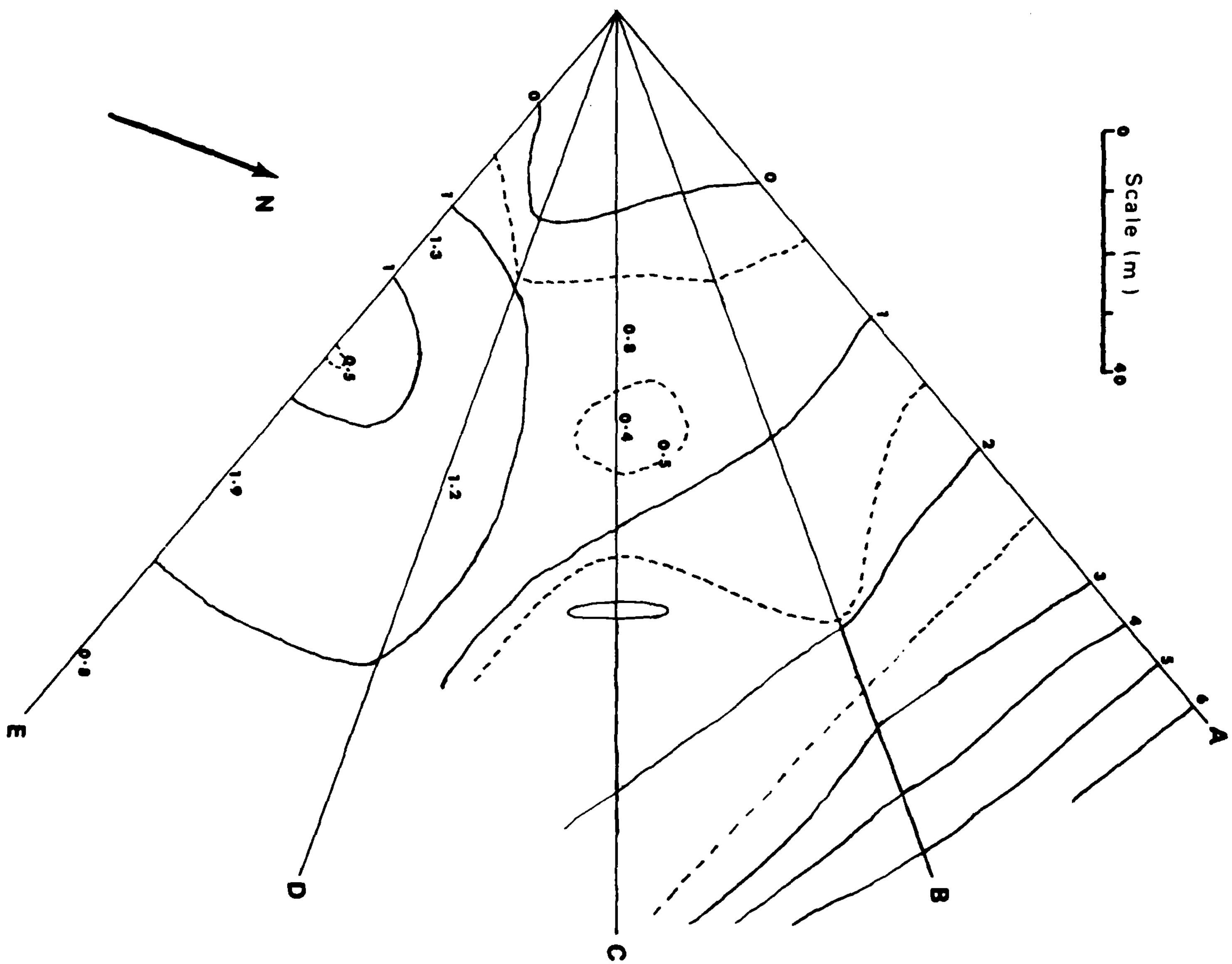


Figure 28. The bathymetry at Sight Point Station. Isobaths at 0.5, 1.5 and 2.5 metres are shown by dashed lines. The depths are in metres below chart datum at the level of LLWS.

along shore with the first large working crack at 42 m, roughly along the 10 m sounding line. The main working crack, at about 70 m out along line C, is roughly aligned with the deepest part of the depression shown in Figure 26, but, because of the water depth, the bathymetry clearly can have had very little effect on the placing of this crack. This is more likely due to the effects of pressure from off-shore which also causes the depression in the ice surface and the consequent band of flooding outside the crack.

At Cape Martyr 'B', (Figure 27) there is again a fairly smooth, even slope from the beach down to a depth of 20 m at a distance of 90 m off shore. While the crack pattern shown in Figure 24 is slightly more complex than that at Delta Station, it is still generally parallel to the beach with the main working crack at 40 m, roughly along the 3 m depth contour. Outside this crack there is again a zone where the ice is generally depressed below HHWS and which consequently floods at high water.

At Sight Point the bathymetry is more complex (Figure 28), with depths of less than 2 m extending out to about 100 m on the centre line. The crack pattern (Figure 25) in the first 40 m from the beach is approximately parallel to the shore line but beyond that is determined mainly by the bathymetry. The closed curves centred at about 150 m out are cracks running around two large composite floes grounded off-shore on Lines B, D and E, while the cracks angling in towards the shore across Lines C, B and A are following the general trend of the bathymetry between 2 and 6 m. The outer working crack runs outside the grounded ice at about 200 m on Line D, C and B, curving shorewards to the outer crack at about 115 m on Line A. The grounded ice extends to about 250 m on Line E and shallow water extends south of the station for several hundred metres beyond the extremity of Sight Point.

Two further observations should be made at this point. The crack pattern measured in 1978 along the centre survey line (Line C) at Delta and Sight Point Stations were generally within two or three metres of the locations found in 1979, with the exception of the diagonal cracks at Sight Point between 90 and 120 m on Line C. In 1978 these were about 8 m nearer the beach. This difference could well be due to a reduction in the extent of the grounded floes during the summer of 1978. Secondly, no examples were found of blocks in the tide crack region which had been turned up on edge. Wilson (Personal Communication, 1979) suggested that this might happen due to the hinging action of the tidal rise and fall and that extra compressive forces might be brought to bear on the cables by this mechanism. In the only case in which we found a block apparently turned on edge we decided after further examination that the formation had originated with a wide crack becoming filled with snow, later flooded and then refrozen. As will be seen later, it is doubtful that a cable could be crushed solely by the pressure of the edge of an ice block as the surface hardness found for the ice in situ is too low.

TEST CABLE ARRAYS

We eventually laid test cable patterns in only three stations because of the delay in 1978 in the development of a shore lead sufficiently wide to install them by boat. The centre cable was laid at right angles to the line of the beach, the rest being disposed in a fan shaped pattern at 20° intervals on each side. Five trenches were dug in the beach starting from the survey marker and extending about 2 m below low water (Figure 29). They were approximately 0.5 m deep with the bottom 0.2 m being cut into frozen gravel. We found these depths were the greatest we could cut with a party of 6, starting at high water from the water's edge and following the level down as the tide ebbed. If only one trench is needed for an installation, such a pick and shovel party could probably increase the depth of the trench into the permafrost by another 0.2 m, but not much more than that since the frozen ice-gravel mix is exceedingly stubborn. Extending the trench below the water line is not really feasible without mechanical and explosive devices used by a full team of divers, or by using powerful equipment such as front-end loaders or drag ploughs. While refilling the trenches, we took samples of the gravel from the bottom of the trench and from the spoil heap at intervals of 3 m.

The cables were thus protected across the intertidal zone of the beach by the 0.2 m slot into the permafrost, and by the tamped down gravel above them. Beyond the low water level the cable was laid open onto the sea bed from a small open boat (Figure 30). The boat was kept on line by using a levelling instrument from the survey marker, the distance along the line

Figure 29. The timer pit and trenches cut into the gravel at Sight Point Station.

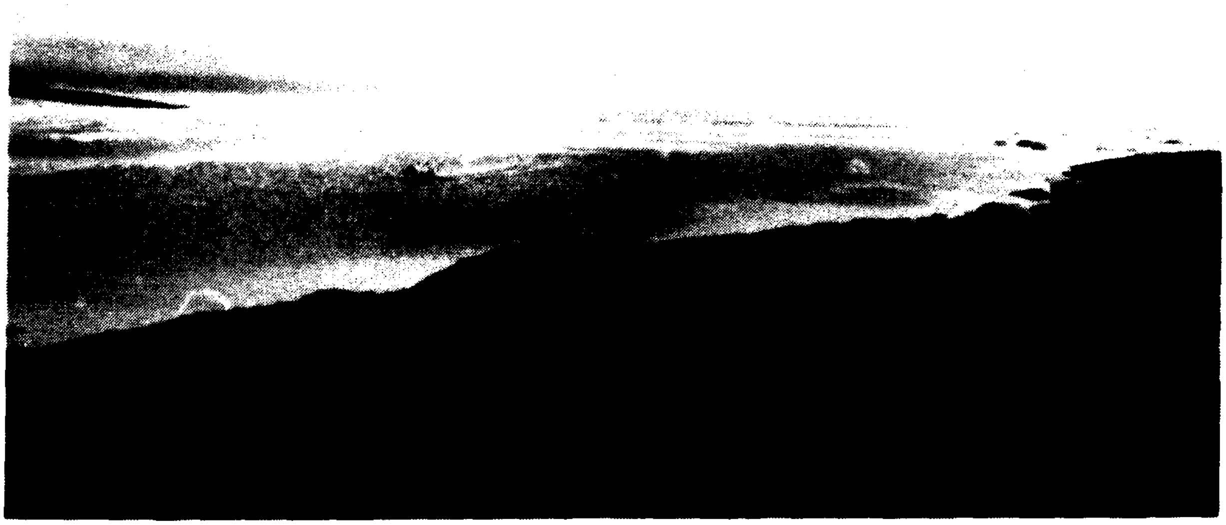
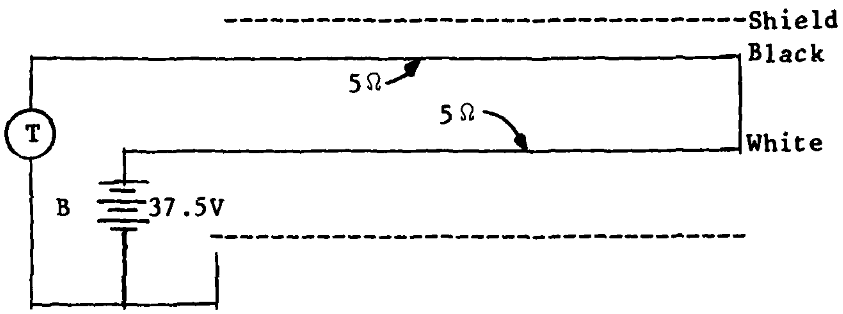


Figure 30. Laying cable on Line E at Sight Point Station. The heavy grounded ice lying across the lines of Cables D and E may be seen in line with the boat.

being checked every 10 m using distance marks previously attached to the cable itself. A small echo-sounder provided a continuous record of depth over the length of the cables. The outer ends of the cables were secured to small Danforth type anchors to prevent their being dragged out of position.

We used a light 2-conductor shielded cable with a breaking strain of 1.8 x 10^3 N (400 pound force). The conductors and the



shield were connected as shown in circuit with T, a timer made by Industrial Time Corporation, and B, a composite battery consisting of 50 lithium cells giving 37.5 V and having a capacity of 14 A.h. The pulsed timer drew a current of 2 A during a pulse lasting 0.6 ms every 10 s, i.e. a mean current of 0.12 mA and an equivalent resistance of 0.3 MΩ . The timers used were calibrated over a period of 700 hours and the uncertainty for the times recorded is estimated to be less than ±2 hours.

Each battery and timer was enclosed in a section of PVC pipe and the ends sealed with a threaded cap. The leads were taken through a watertight plug in one end and then the five pipes for each station were wrapped in polythene and buried about one metre deep in gravel at the survey mark.

The timer is designed to stop whenever the potential across it falls below 8 V. A break in the cable causing an open circuit between the two conductors will cause an immediate stoppage. A dead short across the battery, caused by crushing damage bringing either the two conductors or the conductors and the shield together, will also cause an immediate drop in voltage across the timer to below its operating value. The last possibility is a short, via the sea water, caused either by a complete break or by damage to the insulating cover. In this case a current which was measured to be typically about 50 mA will flow and the voltage will be insufficient to supply the current of about 2 A which is drawn by the timer pulse. In any of these cases the timer gives a good estimate of the time of the damage to the circuit.

The batteries and timers were recovered between 30 August and 1 September 1979, the data on circuit state before recovery being given in Table 2.

TABLE 2

CIRCUIT VALUES BEFORE RECOVERY OF CABLES

STATION	CABLE	RESIDUAL VOLTAGE (V)	RESISTANCE (Ω) B-W	B-S	W-S	REMARKS
DELTA	A	0	OC*	OC	OC	
	B	0	OC	OC	OC	
	C	18.0	OC	OC	OC	
	D	0.6	OC	OC	OC	
	E	0.1	100	5000	5000	
CAPE MARTYR 'B'	A	0.01	1	1	1	
	B	0.05	5000	2500	3500	
	C	0.01	0	5000	5000	Battery case deformed
	D	0.01	20000	20000	2	Timer damaged
	E	0.12	1	1	1	
SIGHT POINT	A	0	0	0	0	
	B	0.2	OC	OC	OC	
	C	18.0	OC	OC	OC	
	D	0	0	0	0	Battery case deformed
	E	0	1	2	2	Timer damaged

* 'OC' = Open Circuit

The cables were recovered from the beach end with surprising ease, since no permafrost had formed around them in the slots cut in 1978 and they were covered only by loose gravel. There were no breaks or any apparent damage to any of the cables between the timer pits and the low water line. At Delta and Sight Point Stations most of the off-shore ends of the cable were recovered out to the anchors by grappling from a small boat. Five cables were recovered completely and another two out to about 100 m where they had to be cut as the ends were caught under grounded ice. The outer ends of the other three cables could not be found. At Cape Martyr Station 'B' the high winds of the night before our visit had piled up ice to a height of 6 m on the low water line and the cables were recovered only down to the line of the ice, which was about 20 m from the timer pit (Figure 31). The loose ends of two of the cables were found while the other three disappeared, apparently still unbroken, under the heavy ice. Difficulty in finding any place to launch the boat, and the rough water conditions off the beach, prevented us from dragging for the outer ends of the cables. The times of the first break in each circuit and the location of breaks in the cable are given in Table 3.

There are wide variations in the effective life of the cables, two of them lasting only 3 days. In view of the conditions we observed on the beaches at the time of laying, the failures of these two are considered to be circuit malfunctions rather than the result of cable damage. Even if these two values are included there is still a significant difference (0.99 probability by *Fisher's 't' test*) between the mean life of the test cables at Delta Station and at the other two. Neglecting the two anomalous values, the mean lifetime at Delta Station was 234 $\pm$ 20 days and at the other two stations 65 $\pm$ 16 days i.e. over the winter of 1978-79 a cable laid at the Delta site would have had 3 or 4 times the chance of staying in operation than one at either of the other two.

There was no significant difference between the measured lifetimes at Cape Martyr 'B' and Sight Point Stations, a result which is a little surprising at first sight because of the great difference in the exposure to pressure from off-shore ice and along-shore movements at the two stations.

Figure 31. Rubble pile at Cape Martyr Station B on September 1979. All five cables disappeared under this wall which extended more or less at the same height for five kilometres along the south shore of Cornwallis Island from Cape Martyr to Sight Point.

TABLE 3
TIME OF CIRCUIT BREAKS AND LOCATION OF CABLE DAMAGE

STATION	CABLE	DATE	TIME (Z)	INTERVAL FROM HW (hrs.)	DISTANCE OF BREAKS FROM SURVEY MARK (m)	REMARKS
DELTA	A	790604	0408	3.1	31	Rest of cable recovered.
	B	790322	2030	3.9	None found	Conductors broken at 28 m. All cable & anchor recovered.
	C	790413	1910	0.1	None found	Conductors broken at 21.9 m. All cable & anchor recovered.
	D	780822	1847	2.3	21.0, 23.1	All cable & anchor recovered except for 2.1 m length.
	E	790305	1812	5.0	27.0	Off-shore end not recovered except loose length of 10 m.
CAPE MARTYR 'B'	A	790103	2210	1.2	20.2	All cables buried by ice rubble. Off-shore ends not recovered.
	B	780912	0021	5.8	26.4	
	C	781005	1903	2.8	20±5	
	D	781112	1553	5.2	None found	
	E	780902	0540	0.4	None found	
SIGHT POINT	A	781116	2055	0.2	11.3, 13.6	No cable recovered beyond 13.6 m.
	B	780823	1520	1.2	9.4, 18.8, 28.3	Recovered cable out to 81 m & cut intentionally.
	C	780105	2040	1.4	28.3	Recovered to 103 m & cut intentionally.
	D	780902	1318	1.1	23.5	All cable & anchor recovered.
	E	790101	0756	1.0	55.0	Recovered all cable except short length under block near shore.

CAUSES OF CABLE FAILURE

Wilson (Personal Communication, 1978) suggested that cables could be crushed to the point where they lost electrical integrity by the pressure of large blocks of ice, turned on edge by the 'hinging' action of successive tidal rises. We found no evidence of any such tilting of iceblocks in the near-shore zone at any point along the 30 km of beach examined during this work. A series of in situ hardness tests of the ice (see below) indicate that it is doubtful if any armoured cable of the type normally used could possibly be crushed by ice pressure alone. The mean hardness value found for the bottom of the ice was 4 $kgf.cm^{-2}$, (340 kPa), which is insufficient to break such a cable either in direct compression or in shear.

The only mechanism by which a cable could be crushed or sheared by the pressure of the ice cover would appear to be that in which the two sides of the 'nut-cracker' are armed with rocks or large gravel pieces. Wilson (Personal Communication, 1978) suggests that this may have happened to one cable which was laid over a sea bed consisting of cobbles about 30 cm in diameter. If one of these were frozen into the undersurface of the ice at low tide, the maximum sustainable force on the ice-cobble combination becomes (crushing strength of ice) x (cross-sectional area of cobble), i.e., $4 \times \pi \times 15^2 = 2.8 \times 10^3$ kgf (2.8×10^4 N). A cable nipped between the cobble and a rock on the sea bed, during a later falling tide, might well have this maximum force acting on only one or two square centimetres. In this case, the maximum pressure exerted on the cable would be of the order of 10^3 $kgf.cm^{-2}$, or 100 MPa, sufficient to crush most cables.

The beaches used during this experiment had few pieces of rock of this size or bigger. Samples from all three stations, taken from the trench bottoms and from the spoil removed from the trenches, indicate that the gravel was reasonably well sorted, with about half of it by weight having a maximum diameter within the range of 1 to 3 cm. The data given in Appendix A and Figures A1 and A2 show that there was little difference between samples from different stations, or between those from the beach surface and the trench bottom except for a slightly higher ratio of fines at Delta Station and in the trench bottoms. We saw no indication during this experiment of damage to cables by gravel frozen into the ice cover.

We found in fact that <u>all</u> of the cable breaks examined during this experiment were tension failures. In several cases the outer insulation layer was unbroken while the conductors and shielding had been pulled apart. In other cases the break was complete but there were obvious signs that the insulating cover had been stretched before failure. We must therefore look for a mechanism which can apply tensile stresses exceeding 2000 N (450 pounds force) to the cables. Almost without exception the breaks we found were in the zone between the low water line and the outer edge of the zone in which the ice came into contact with the cables at some state of the tide (Zone B, Table 1). The breaks did not in general occur at the actual position of the tide cracks.

We suggest that if the ice touches the cable on the sea bed the cable may become frozen onto the bottom of the ice blocks at low water. A rising tide will then tend to open the crack at the bottom and apply tension to the cable over the length lying between the main points of adhesion. The cable will then part in tension at the weakest point which may or may not be immediately under the crack itself.

The magnitude of the tensile force exerted may be approximated using a simple beam model. Consider a beam of ice with a rectangular cross-section and unit width. For simplicity the beam may be regarded as a simply supported uniformly loaded beam of unit width, the reaction at each end being taken by the sea bed, or by the sea bed at one end and by the buoyancy forces considered as acting at the seaward extremity. Figure 32 indicates the dimensions.

Assuming even loading caused by the difference between the weight of unit length of the beam and the buoyancy of the submerged portion we have the bending moment of M at L/2

$$M = \frac{(t\rho_i - z_w\rho_w)gL^2}{8},$$

the moment of inertia $I = \dfrac{t^3}{12}$,

and the tension required at height z above the lower surface of the ice

$$T_z = \frac{M\,z}{I}$$

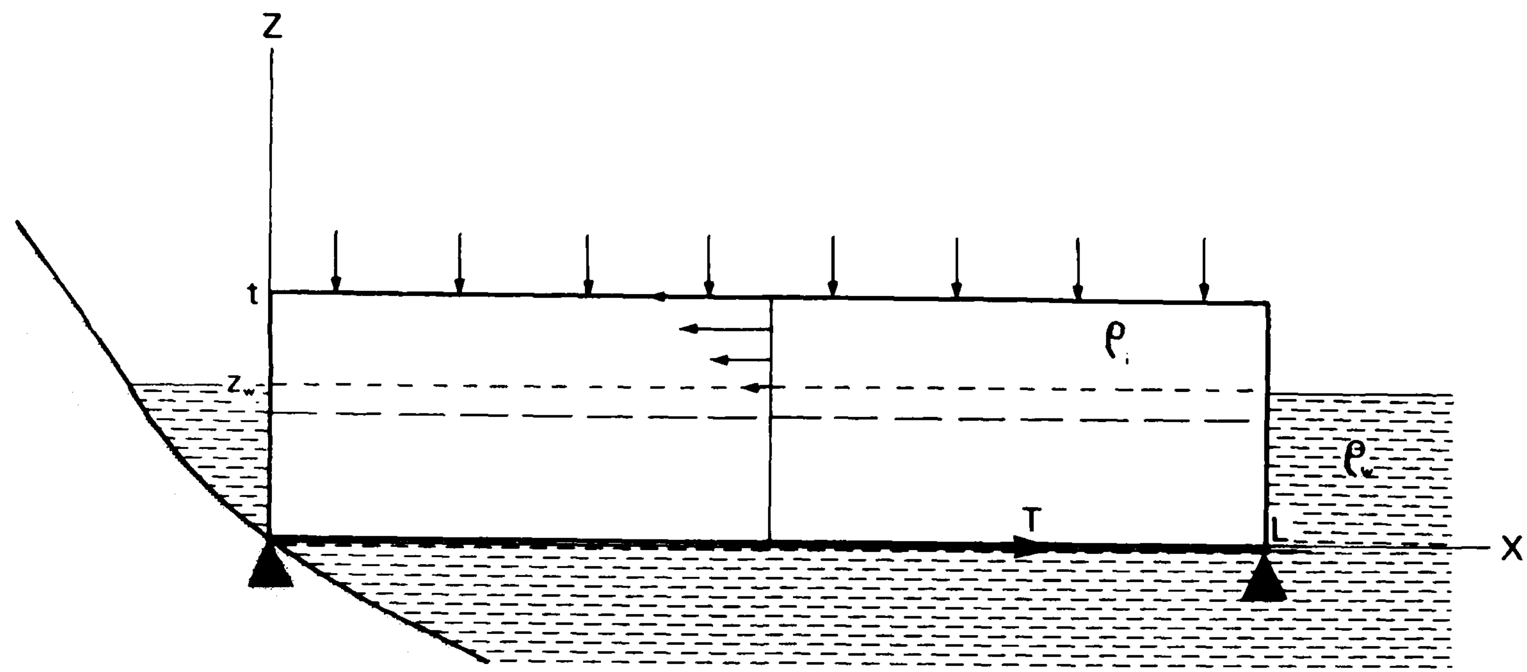


Figure 32. Simple beam model for estimating the tension in a cable frozen to the bottom of sea ice which is cracked.

where L is the total length

ρ_i and ρ_w are the densities of ice and water respectively, and

t is the ice thickness.

Now suppose that the beam is split vertically at L/2, the mid-point of its length, but that it is held together by a cable frozen into the lower surface of the block along its length. Then the cable must sustain the sum of the tensile forces which act in the lower half of the unbroken beam, this tension T being given by

$$T = \frac{M}{I} \int_{o}^{t/2} z.dz$$

$$T = \frac{3(t\rho_i - z_w\rho_w)gL^2}{16t}$$

Inserting typical values, for a block initially 10 m long and 2 m thick, with $\rho_i = 0.8 \times 10^3$ kg.m^{-3}, $\rho_w = 10^3$ kg.m^{-3} and $z_w = 1$ m we have $T = 5.5 \times 10^4$ N (1.2×10^3 pounds force), or about 5 tonnes force for each metre width of the block. The tensile forces exerted can certainly be an order of magnitude or more larger than the breaking strain of most cables.

A further possible source of damage to cables is the disturbance to the beach itself and the cable buried under it by ice driven into the beach by pressure of ice off-shore or of wind. At all three stations evidence was found of this phenomenon, particularly after the high winds of 31 August 1979. Some of the gravel berms pushed up by the ice were a metre high along the Old Village section of the shoreline while those at Sight Point and Delta Stations were generally about half that height. However the depth of the scrape marks in the beach was much less than this; as nearly as could be determined they were only about 10 cm deep, or at most down to the permafrost level.

The impact on the beach of relatively small floes (10 m diameter) is insufficient to do more than raise a small gravel berm. For example the kinetic energy of a floe 100 m^2 and 2 m thick moving at the relatively high velocity of 0.5 m.s.$^{-2}$ is about 2.5×10^4 J, while the potential energy of a 10 m long berm 1 m high is about 5×10^4 J, and this takes no account of the increase in potential energy of the floe itself as it rides up the beach. Massive beach effects which are likely to damage cables require more energy than is available in the inertia of individual moving ice floes; indeed the most radical changes are found in areas where an extensive ice cover is being forced into the beach by the integrated wind drag over miles of closely packed ice. Kovacs and Sohdi (1980) give a good survey of this type of ice action, which on a gently sloping beach may force ice several hundred metres inshore. Even in these cases of massive ice-push, little damage appears to be caused to the beach itself although structures in the area may be completely destroyed. On a more steeply sloping beach, the ice as it is forced ashore tends to over-ride its leading edge and to form the kind of rubble pile which we observed in September 1979, while leaving the upper part of the beach free of ice. Our experience indicates that a cable buried even a few centimetres in the frozen layer of the beach gravel will not usually be disturbed by ice action on the scale seen in 1978 and 1979 and that the same will probably be true even when the scale of ice movement is considerably larger.

A cable lying open on the sea bed is in a vulnerable position if the water is sufficiently shallow to allow ice to ground at low water or for the keels of heavy floes to scour the bottom. The latter is the most likely cause of cable failure around the time of first freeze-up when the new sea ice is still thin enough for such floes to be driven through it by wind or current. However most of the breaks we encountered seemed to be the result of the cable's freezing onto the bottom of the ice as the latter grounded on the sea bed at low water. In our case, a shallow trench out to the point where the water was more than 2 m deep at LLWS would probably have sufficed to prevent any cable damage, while in areas where heavy floes may be driven along the beach it might be necessary to trench out to a depth of 3 or 4 m.

ANCHOR ICE

A further factor which must be considered in the survival of cables is the existence of a belt of anchor ice along the shore just off the beach (Figure 33). Sadler and Serson (1981) examined this belt and discovered that it was made up of fresh water ice. It extends two or three metres out from the low water line and is found along much of the beach. In August 1978, for example, about 70% of the beach over a distance of 30 km had this strip along it. It was 30 to 50 cm thick and was bonded to the

Figure 33. Belt of fresh-water anchor ice at Sight Point Station. The upper surface is clear of gravel but is scored by the movement of floes above it. The floes in the middle distance are about 1.5 m thick and have gravel frozen into their lower surfaces. The photograph was taken at the time of LLWS.

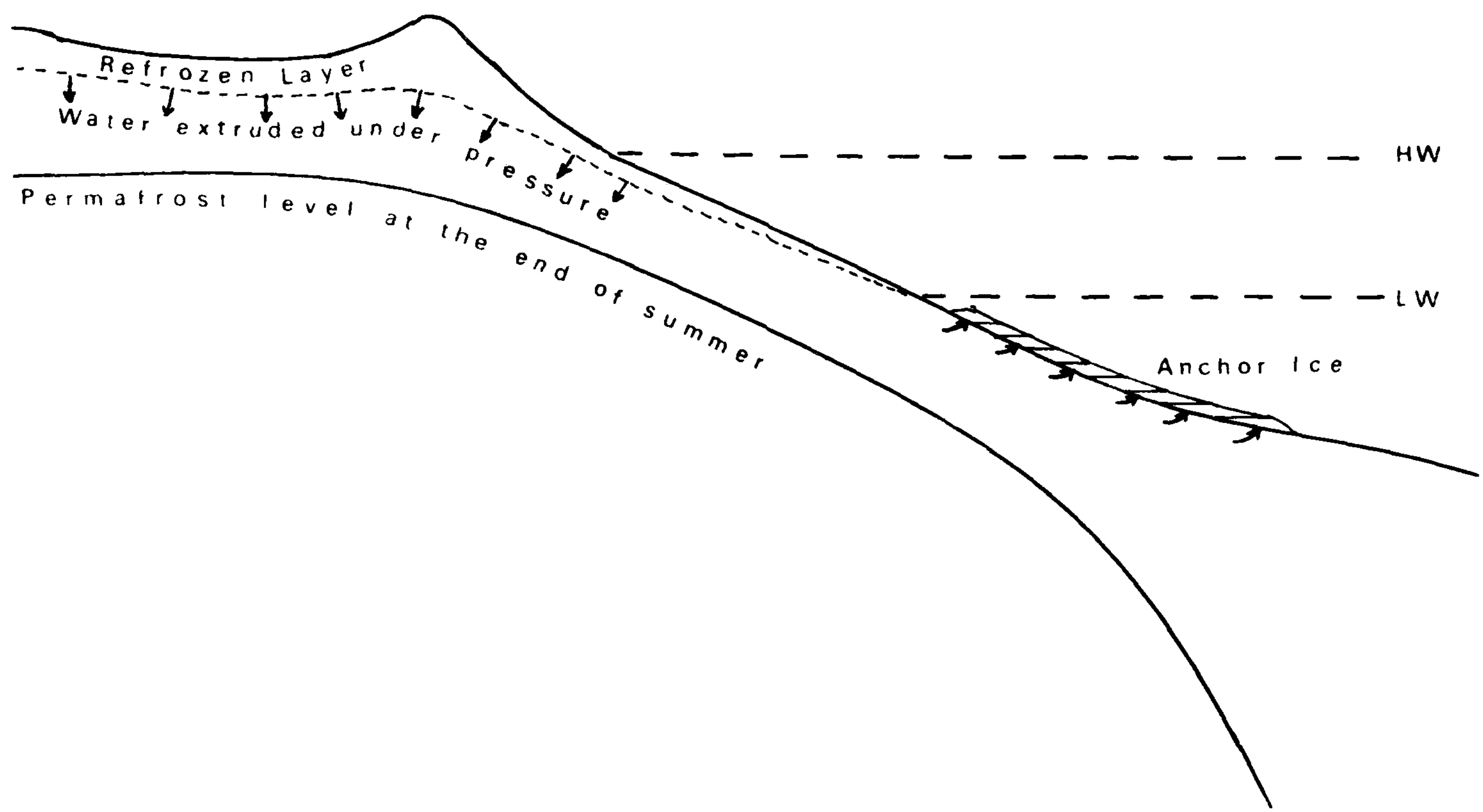


Figure 34. Diagram illustrating the suggested mode of formation of fresh-water anchor ice on a gravel beach. Fresh water confined in the duct formed by the freezing of the surface gravel is forced out through the sea bed.

gravel of the sea bed, the upper surface being flat, smooth and usually free of gravel. The surface was scored by the gravel frozen into sea ice which had over-ridden it, but the anchor ice itself had no gravel inclusions. We have suggested that the belt is formed by runoff water in the beach gravel forced out of the duct which forms with the first frost (Figure 34).

Such a belt of ice would obviously provide protection to cables running beneath it but it would also reduce the horizontal friction forces acting on the sea ice as it is pushed in towards the beach. This may increase the height of a rubble pile on the beach or the extent of the gravel push, but the effect is likely to be of most concern to the users of artificial islands in the Beaufort Sea, for example.

The whole process is obviously sensitive to a number of parameters, such as the amount and the rate of run-off and the date of the first refreezing of the upper layer of the gravel, and the extent of the anchor ice is likely to vary widely from year to year. Much more would have to be known about the process before it could be used as a criterion for choosing cable sites but such a formation, either natural or artificial, would provide a great deal of protection for a cable in a zone where it is particularly vulnerable.

IN SITU ICE STRENGTH TESTS

The problem of characterizing the mechanical strength of sea ice is one of great practical importance since it impinges on the design and operation of industrial installations such as artificial islands, drill ships, loading points etc. Unfortunately it is unrealistic to hope to arrive at a single constant which will allow us to calculate the compressive strength of ice. Goodman (unpublished manuscript, 1980) observes that the value obtained by a normal strength test is a function of a wide variety of variables including salinity, temperature, freezing history, crystal size, time lapse before testing, rate of application of stress, etc. In situ testing removes only a few of these variables and the results cannot be applied directly to a general situation. For example, most of the values for compressive strength given in the literature have been measured by some form of expanding ring or bore-hole jack set in a vertical hole drilled in the ice. Because of the *anisotropic* structure of sea ice the value for horizontal compressive strength cannot be extended to vertical strength, particularly as the structure of the lower surface of the ice which is of interest here differs a great deal from that in the body of the ice cover.

In the case of a cable being crushed between the ice and the sea bed the conditions are a little more predictable than in the general case. The temperature and salinity are fairly constant and in situ values for the vertical crushing strength of the lower surface may be more generally applicable than those in the literature. We adapted a calibrated proving ring apparatus to measure the crushing strength of the lower surface of the ice directly, using a balanced bar suspended from a steel wire passing through a vertical hole drilled in the ice to force several different dies into the lower surface (Figure 35). Spherical and conical shapes were used in the field but we found that the conical heads gave consistently high values. Laboratory tests on sea ice and on paraffin wax blocks indicated that the probable reason for this is that when used on a semi-plastic material such as ice, the conical head extrudes crushed material around the circumference as it begins to penetrate. The result is a raised annulus of displaced material which increases the effective projected area of the bearing surface of the head above the value which is calculated from the amount of penetration recorded, and this results in too high a value for the calculated crushing strength. The spherical head in contrast produced a clean depression and the measured penetration gave a good estimate of the projected area.

The results from ball penetration tests taken at six different locations, at different seasons of the year and over a two year period are summarized in Figure 36 where the load* in $kgf.cm^{-2}$ is plotted against the projected area calculated from the measured penetration. It will be seen that there is considerable scatter when the penetration is small but that the envelope of the points narrows rapidly with increasing projected area. The broken line connects points obtained in one series of measurements and shows a steady decrease in crushing strength as the projected area increases. While some scatter is to be expected from observations carried

* 1 kilogram force per square centimetre = 98.1 kPa.

Figure 35. Ice crushing strength testing apparatus. The small spheres shown mounted at the ends of the arm in the lower right hand corner are forced into the lower surface of the sea ice by tension in the suspending wire, the penetration and tension being measured by the distorting ring which straddles the hole drilled in the ice.

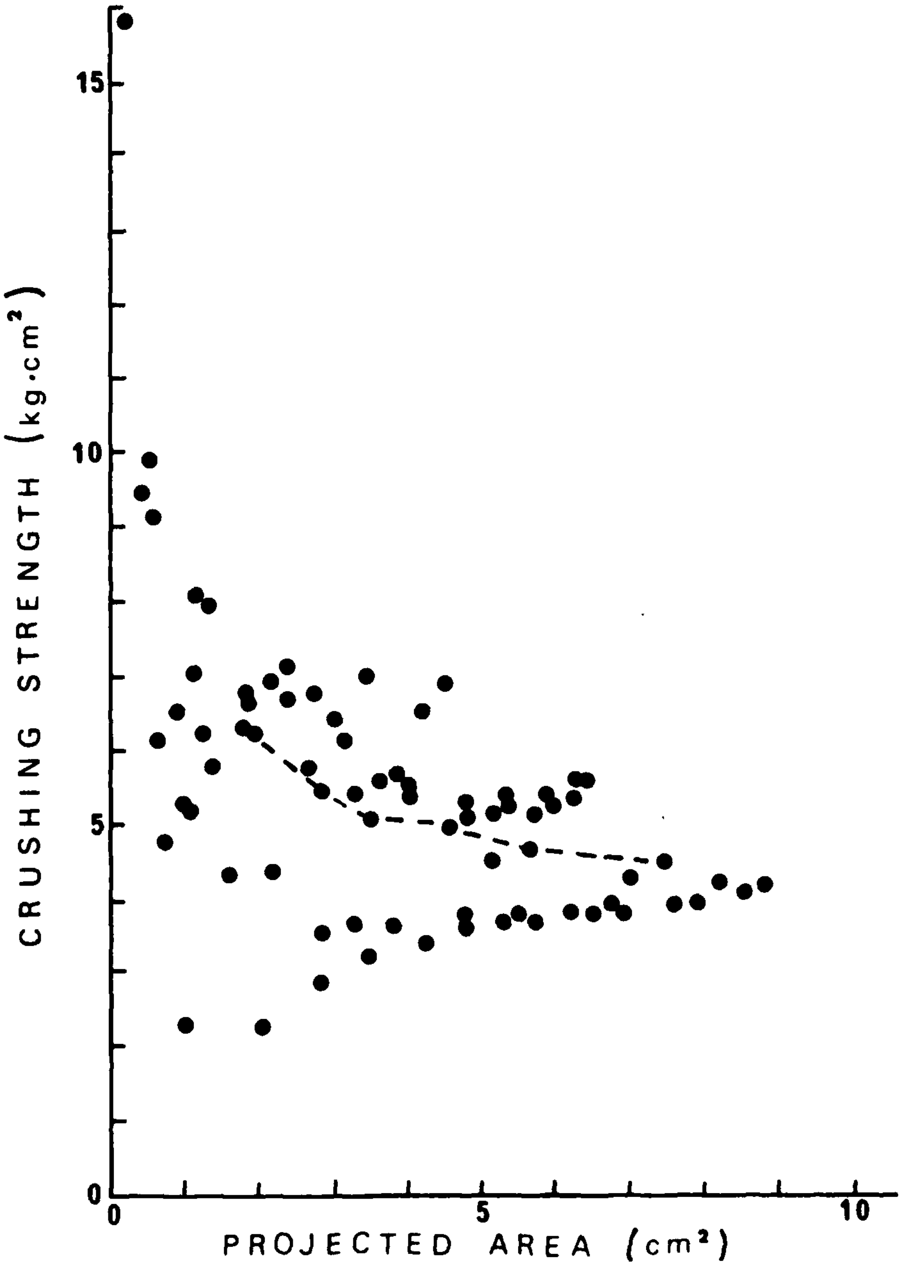


Figure 36. The in situ crushing strength of the lower surface of sea ice plotted against the projected area of the penetrating spheres. The dotted line connects a single series of readings.

out at different places and times, the wide variations which appear when the projected area is less than 2 cm^2 are caused by small scale structural variations in the lower surface of the ice. If the ball is centred on a brine cell for example the penetration for a given applied stress will be larger and a lower crushing strength will be indicated than if the ball is centred on a large ice crystal. This is supported by observations made while diving under the ice, when it is found that a diver can force a thumb nail into the lower surface of the ice at most places; indeed his whole forearm may be forced into the ice of the keel of a pressure ridge. As the projected area increases, the random variations in hardness begin to average out with the crushing strength approaching a value of 4 $kgf.cm^{-2}$ (390 kPa) over larger areas.

The tensile strength of the ice in situ is more difficult to observe directly and we combined relations developed by Frankenstein (1968) and by Graystone and Langleben (1963) to find the tensile strength σ_t from

$$\sigma_t = 29.0 - 53.3\sqrt{\frac{S_i}{1000}\left(\frac{49.985}{\theta_i} + 0.532\right)}$$

where S_i is the salinity of the ice in parts per thousand

θ_i is the temperature in °C at the particular location, and

σ_t is in $kgf.cm^{-2}$.

The salinities were measured by melting 1 cm thick samples cut at 20 cm intervals from a 7.5 cm diameter core obtained with a Sipre coring auger. The salinity was then measured using an Endeco refractive index type salinometer and is considered to be accurate to ±0.10 ppt. The temperatures were measured in a separate 2.5 cm hole drilled near the core hole, the small hole being drilled in 20 cm steps. After each 20 cm was drilled, a thermistor head was inserted and pressed firmly against the ice at the appropriate depth by means of an inflatable bulb. The measured temperature stabilized after about 30 seconds and the values recorded are considered accurate to ±0.02°C. The resulting value of σ_t is accurate to ±0.1 $kgf.cm^{-2}$ plus the uncertainty involved in the expression for σ_t. The results from the Sight Point Station are plotted in Figure 37 where the profile depths are normalized to allow for observations through different ice thicknesses. Six of the profiles agree fairly closely in spite of being

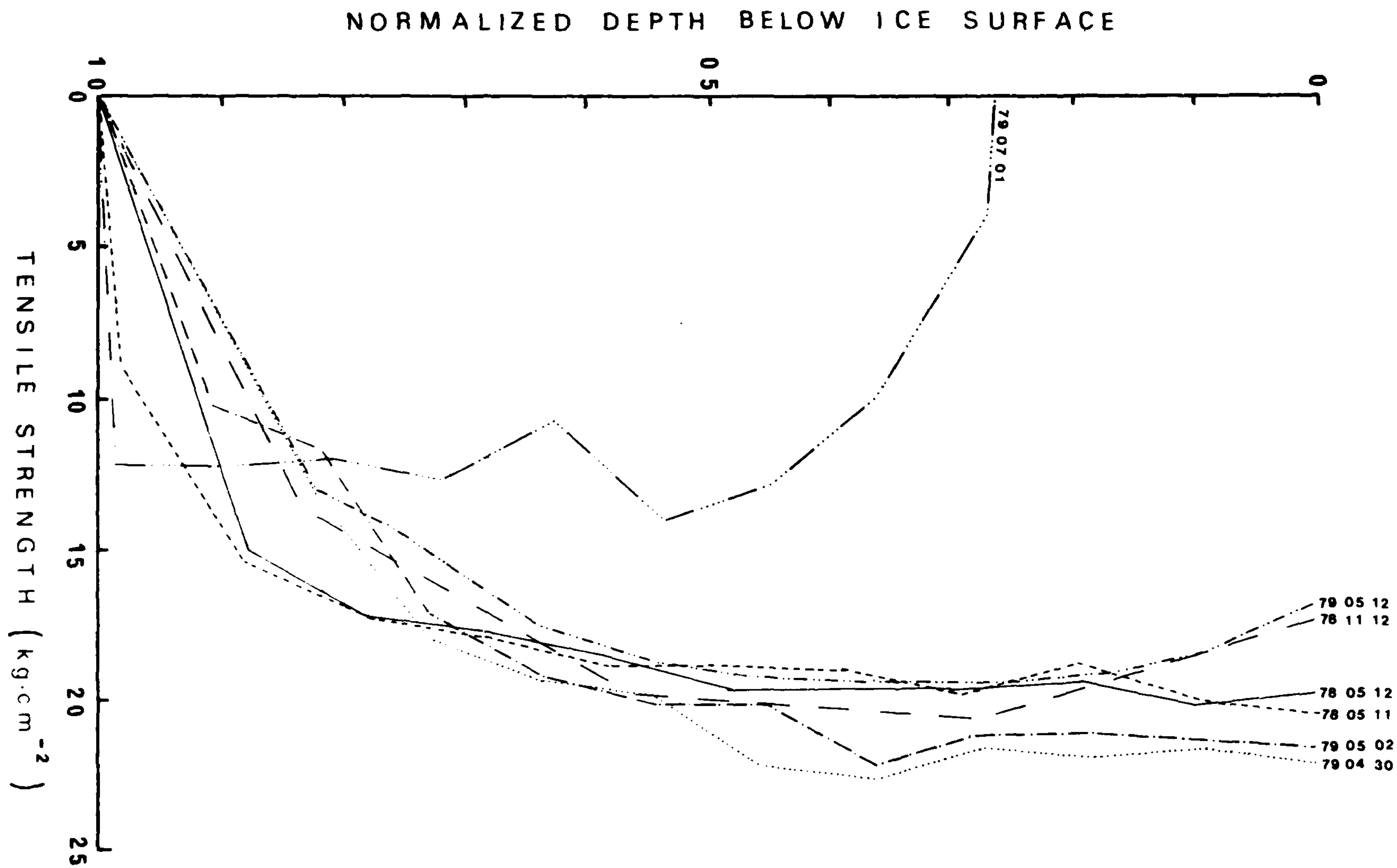


Figure 37. Profile of the tensile strength through the sea-ice at Sight Point Station on different dates. The depths below the upper surface of the ice are shown as fractions of the total thickness.

taken at different seasons. The only one which does not follow the pattern is that taken on 1 July 1979 at a time when the ice was 70% covered with melt pools and the surface ice was candled and rotten, resulting in variable and untrustworthy values of salinity. In general the tensile strength of the ice is 20 ±2 $kgf.cm^{-2}$ (1960 kPa) from near the surface through about 70% of its thickness, and it then falls off to near zero at the lower surface where the temperature is about -1.5°C and the salinity rises to about 8 ppt.

Integrated over the lower half of the ice the tensile strength is about 15 $kgf.cm^{-2}$ (1470 kPa), so that a beam of 1 m width and 2 m depth could support a tension in bending of no more than $1x10^5$ kgf. ($9.8x10^5$N). In practise the maximum sustainable tension is appreciably less than that since the tensile strength at the lower surface, where the bending stresses are a maximum, is about 1/10 of the mean value. In summary, the ice is so weak in tension that a small floe of 10 m diameter will fracture if it grounds as a simply supported beam and the tide then falls a further half metre. The full tension would then be thrown on to any cable frozen into the base of the floe.

The ultimate crushing strength and tensile strength data from all locations are given in Appendix D.

OTHER OBSERVATIONS

Current Profiles

Current profiles were measured at the outer end of each trench in March 1978, using a Marsh-McBurney Electromagnetic Current Meter which records orthogonal horizontal components on paper chart. The probe was mounted on a 10 m aluminum tube which permitted the probe to be oriented by surface observations, while at the same time allowing the depth of the probe to be adjusted in 1 m steps from the lower surface of the ice down to the maximum depth of 7.7 m. Only at Cape Martyr station did we find measurable currents. On 17 May 1978, we recorded an easterly flow of 5 $cm.s^{-1}$ down to 4 m below the ice and a westerly flow of 3 $cm.s^{-1}$ below that. However when the measurements were repeated over six hours on 19 May, at spring tides, the maximum current was only 2 $cm.s^{-1}$, just on the threshold sensitivity of the meter/recorder combination. We conclude that there was no significant effect on the ice by currents in the water.

Grounded Floes

Large grounded masses of ice a hundred metres or so off shore were prominent features at several of the stations, particularly at Sight Point and South Camp Stations. We investigated the structure of two typical examples, one at each of these two stations. The floe near South Camp Station consisted of a single piece of sea ice about 15 m in diameter and 3 m thick which was tilted to an angle of about 70° with the horizontal and supported in this near vertical position by a number of smaller blocks below it. The floe had apparently been grounded in that position for at least one year. A long (9.5 m) core was taken from the main floe parallel to the original ice surface with the object of checking if the strength of the ice had been affected by the drainage of brine down from the high point, i.e. across the 'grain' of the brine channels. The results showed no such effect, the salinity across the full diameter of the flow on a line about 1 m below the original surface being about 1.2 ppt. over the whole core.

The second large piece of grounded ice, off the Sight Point Station, turned out to be a composite of blocks of ice each 2 to 3 m thick. A floe about 10 m in diameter was set horizontally on three more blocks below it. Beneath the 'table top' there was a vacancy about 1 m high and two or three m long. A core taken through the top piece and down into one of the 'table legs' showed that the leg was also composite, made up of two ice blocks each about 2 m thick. These two sets of observations indicate that the large piles of grounded ice are composite structures and probably have a comparatively low density, with large vacancies in the interior, while snow fill on the outside makes up much of the total volume of the pile.

Ablation Measurements and Gravel Strip

One recognized method for speeding up the melting of ice in the spring to assist in the break up of ice cover in a harbour is to cover the surface with a heat absorbing material such as soot or coal dust. The main problems with this method are that coal dust or other absorbent must be transported to the site in the first place and that after use it tends to remain and spread around the area with unknown results to the biota. We decided to test the possibility of using locally available material, beach gravel being the obvious choice as a plentiful, non-polluting medium.

At the end of May 1978 we scattered about 3 tonnes of gravel taken from the beach berm over a strip about 2.5 m wide extending 100 m out from the shore line at Sight Point Station. We found that the ablation rate in this strip was 30% to 50% greater than that for the ice alongside it and we consider that this method would repay further evaluation. The details of the experiment are given in Appendix C.

Ice On and In the Beach

We examined all of the beaches for damage or disturbance by the effects of ice from previous years. Most of the beaches showed the classic signs of ice working described by previous authors (See for example, McCann, 1972). Gravel push was usually about 0.5 m high and kettleholes, which were most numerous around Sight Point, were usually about the same depth. In this area the effects of ice and ice inclusions on the form of the beach gravel were generally of a minor nature and there was little or no indication of any disturbance of the gravel below the permafrost level. As McCann observed in Radstock Bay, major changes in the beach structure or geometry are due to random combinations of circumstances, at intervals which may be as long as 10 years, when an ice free water surface off shore coincides with strong onshore wind and wave action.

Most of the blocks of ice lying on the beach at or above high water level were clean sea ice with perhaps a layer of gravel frozen to the bottom surface. On the open beach west of Sight Point we found one unusual formation; a block about 3 m in diameter and 0.5 m thick which consisted of an ice/gravel concrete, with about a 4:1 ratio of gravel to ice by volume. The block was wedged up at an angle and overhung its support by 2 m. We know of no previous mention of this type of conglomerate in the literature, but it would clearly have much greater strength in compression than ordinary sea ice, and would also be far too dense to float on its own. It probably results from repeated contacts with the sea bed by thickening sea ice, each contact allowing another thin layer of gravel to become incorporated, but in any case it appears to be an unusual event as this was the only example found along 30 km of beach. Alternatively such a block might be formed as part of the permafrost layer, although the mechanism by which it could then be displaced is far from clear.

Stereophotographs

The mounting used for this purpose consisted of an aluminum bar with screw mounts for a Konica Aerial Camera set one metre apart at opposite ends. The bar itself fitted onto a standard survey tripod and could be levelled in the usual way. A 1 m square frame was used to give scale and the pairs of photographs were taken within one minute of each other. The technique showed promise and some of the pairs were of value in interpreting measurements and notes taken at the test sites. More information is given in Appendix B.

CONCLUSIONS

All of the 15 cables laid during this experiment failed, some almost immediately and some after up to 10 months of exposure to ice action, all of the failures occurring in the region of active tide cracks. All of the breaks found in the recovered cables were failures in tension, either in the conductors, the cover, or both. There was therefore no indication of any damage due to direct ice pressure or by 'hinging' of blocks in the tide crack region. There are several mechanisms by which the cables could have been broken in tension, the most likely being the tension applied to a cable frozen into the lower surface of the ice on both sides of an active crack, the cable being parted by the differential tilting of the ice on either side of the crack as the water level changed with the tide.

It is possible for the cable to be crushed by the weight of grounding ice only if both the ice and the seabed are 'armed' with rocks, since the compression strength of the ice itself is two orders of magnitude below that of a typical armoured cable. This circumstance is unlikely to be encountered frequently.

There was no evidence at the Delta and Sight Point Stations of any damage to the cables by ice action on the material of the beach itself, in spite of the fact that the cables had not frozen into position above the high water mark. At Cape Martyr the cables could not be recovered from beneath a large rubble pile but they were undamaged across the beach to the timer pit. Damage to the beach, even by the large amount of ice driven up onto it on 30 September 1979, was confined to the upper few centimetres.

The following recommendations are made for laying cables across a beach zone when heavy trenching equipment is not available. None of them is new.

1. Select a beach with no obvious large ice inclusions or signs of heavy ice push.
2. If possible, the beach should be protected from long-shore movement of ice, either by the geometry of the shore or by shoal water near the cable.
3. Bury the cable below the summer permafrost level above the low water line. This is probably easier to do at a delta station because of the larger proportion of fine fractions.
4. Lay the cable below the low water line in a trench cut deep enough to prevent the cable from coming into contact with the lower surface of the ice. This normally will depend on the amount of gravel which is removed each year by freezing onto the bottom of the sea ice. Generally we suggest that a trench 30 cm deep will provide protection for several years provided the area is not subject to scouring by the deep keels of heavy floes. The length of the trench should obviously be as short as possible and a fairly steep slope to the sea bed is desirable.
5. It may be possible on rocky shore lines to find a natural crevice which will provide protection to the cable over most of the critical zone.

<u>Other Techniques</u>

We suggest the possibility of developing a method of forming an ice shield for cables. Above the low water level it is easy to build up a coating of fresh water ice above the cable when a convenient source of fresh water can be found and the air temperature is sufficiently low. Such a covering would provide a great deal of protection against any kind of surface action on the beach. It might also prove possible to extend this ice protection below the low water line by laying a perforated hose along with the cable and then bleeding fresh water through it to form a shield above the cable.

In the case of a permanent or multi-year installation, it is clearly worthwhile to increase the protection for the cables. This could be done by building a permanent mole over the run of the cable. An example of this technique is the Tide Hut jetty in Resolute Bay, which was constructed in two months by one summer student using a small bulldozer and which has lasted unharmed for over ten years to the present. Such a mole might well be carried out to depths of two or three metres when gravel is readily available. One of the oil companies has protected pipe-lines across the beach by building up an ice cover right over it and then insulating the ice with a thick covering of gravel.

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APPENDIX 'A'

ANALYSIS OF GRAVEL SAMPLES FROM THREE BEACH STATIONS

METHOD OF SAMPLING

At each station gravel samples were taken from the centre trench while cable laying was in progress. We removed samples from the spoil at the timer pit and at intervals of 3 m along the trench and also from the trench bottom at each point. The samples, each weighing about 4 kg, were stored in polythene bags and later spread to dry. We sorted for size with a hand powered shaker and a set of 8 sieves ranging in mesh size from 100 mm to 0.038 mm. The results are given in Table A1, as the mass in grams between consecutive mesh sizes and also as a percentage of the total mass of each sample. The sample number in Column 1 is a code consisting of a letter indicating the station and a consecutive number. The location from which the sample was taken is given in Column 2.

DISCUSSION

Distribution histograms are given, in Figure A1 for all spoil samples and all trench bottom samples, and in Figure A2 for all samples at each station. The differences are unimportant. Figure A1 shows a slightly higher proportion of fines in the trench bottom samples when compared to those from the spoil and Figure A2 a slightly higher proportion of fines in the samples from Delta Station than in those from the other two stations but in neither case would the difference have any effect on breaking cables.

TABLE A1

SORTED GRAVEL SAMPLES

SAMPLE NUMBER	LOCATION. DISTANCE FROM MARK (m)	TOTAL MASS (gm)	MASS (gm and %) FOR EACH MESH (mm)							
			31.5 to 100	9.5 to 31.5	3.35 to 9.5	1.0 to 3.35	0.30 to 1.0	0.106 to 0.30	0.038 to 0.106	0.038
D1	Surface 1	3578.1	879.8 24.6	2346.1 65.6	330.5 9.2	15.9 0.4	3.4 0.2	1.3 0.1	0.8 0.0	0.3 0.0
D2	Bottom 3	3881.0	468.6 12.1	1453.6 37.5	685.8 17.7	480.9 12.4	370.0 9.5	377.9 9.7	43.7 1.1	0.5 0.0
D3	Spoil 3	4053.3	57.2 1.4	2442.5 60.3	738.6 18.2	275.4 6.8	161.7 4.0	284.5 7.0	89.4 2.2	4.0 0.1
D4	Bottom 6	4133.4	1122.4 27.2	1675.0 40.5	442.6 10.7	208.5 5.0	269.5 6.5	306.5 7.4	103.5 2.5	5.2 0.1
D5	Spoil 6	4398.5	437.2 10.8	1934.9 44.0	881.8 20.1	458.6 10.4	540.4 12.3	104.7 2.4	4.2 0.1	0.7 0.0
D6	Bottom 9	3388.9	152.0 4.0	741.9 21.9	644.4 19.0	678.7 20.0	591.1 17.4	487.9 14.4	88.3 2.6	4.6 0.1
D7	Spoil 9	4972.1	1222.8 24.6	1588.7 31.9	627.3 12.6	584.7 11.8	554.7 11.2	345.5 6.9	47.1 1.0	1.3 0.0
D8	Bottom 12	3921.2	504.5 12.9	944.4 24.1	867.7 22.1	466.9 11.9	500.0 12.7	500.6 12.8	123.5 3.2	13.6 0.3
D9	Spoil 12	4182.6	211.5 5.1	1139.9 27.3	602.4 14.4	581.6 13.9	775.1 18.5	685.3 16.4	169.1 4.0	17.7 0.4
D10	Bottom 15	3910.0	556.5 14.2	1678.3 42.9	208.1 5.3	248.9 6.4	468.4 12.0	639.3 16.4	104.2 2.7	6.3 0.2
D11	Spoil 15	3927.3	797.7 20.3	1451.7 37.0	434.4 11.0	376.6 9.6	431.2 11.0	351.7 9.0	80.1 2.0	3.9 0.1

TABLE A1 (Cont.)

SAMPLE NUMBER	LOCATION. DISTANCE FROM MARK (m)	TOTAL MASS (gm)	MASS (gm and %) FOR EACH MESH (mm)							
			31.5 to 100	9.5 to 31.5	3.35 to 9.5	1.0 to 3.35	0.30 to 1.0	0.106 to 0.30	0.038 to 0.106	0.038
D12	Bottom 18	3221.3	0.0 0.0	605.9 18.8	710.2 22.1	559.1 17.4	957.8 29.7	368.7 11.5	18.5 0.6	1.1 0.0
D13	Spoil 18	3757.7	144.8 3.9	1739.0 46.4	1495.4 39.8	255.9 6.8	50.7 1.4	52.1 1.4	14.5 0.4	Trace 0.0
M1	Surface 0	4276.7	1691.8 39.6	2584.2 60.4	0.0 0.0	0.0 0.0	0.7 0.0	0.0 0.0	0.0 0.0	0.0 0.0
M2	Spoil 0	3777.4	961.0 25.3	2500.3 66.1	266.3 7.0	48.4 1.3	1.4 0.0	0.0 0.0	0.0 0.0	0.0 0.0
M3	Bottom 3	4498.9	41.5 0.9	2529.0 56.2	1270.8 28.3	386.4 8.6	215.2 4.8	55.6 1.2	0.3 0.0	0.0 0.0
M4	Spoil 3	3792.7	0.0 0.0	1804.3 47.6	1779.7 46.9	160.5 4.2	46.6 1.2	1.2 0.1	0.4 0.0	0.0 0.0
M5	Bottom 6	NO	SAMPLE.	TRENCH	BOTTOM	ON PERMAFROST.				
M6	Spoil 6	4568.3	44.7 1.0	1746.9 38.2	1500.7 32.9	721.8 15.8	528.1 11.6	23.2 0.5	2.5 0.1	0.4 0.0
M7	Bottom 9	NO	SAMPLE.	TRENCH	BOTTOM	ON PERMAFROST.				
M8	Spoil 9	3605.7	0.0 0.0	1851.8 51.4	1248.0 34.6	395.3 11.0	90.3 2.5	18.2 0.5	1.5 0.0	0.6 0.0
S1	Surface 0	3800.2	468.0 12.3	3050.9 80.3	279.8 7.4	0.7 0.0	0.8 0.0	0.0 0.0	0.0 0.0	0.0 0.0

TABLE A1 (Cont.)

SAMPLE NUMBER	LOCATION. DISTANCE FROM MARK (m)	TOTAL MASS (gm)	MASS (gm and %) FOR EACH MESH (mm)							
			31.5 to 100	9.5 to 31.5	3.35 to 9.5	1.0 to 3.35	0.30 to 1.0	0.106 to 0.30	0.038 to o.106	0.038
S2	Bottom 3	3172.4	0.0 0.0	3109.3 98.0	61.2 1.9	0.7 0.0	1.2 0.0	0.0 0.0	0.0 0.0	0.0 0.0
S3	Spoil 3	3718.8	0.0 0.0	3528.7 94.9	188.5 5.1	0.7 0.0	0.9 0.0	0.0 0.0	0.0 0.0	0.0 0.0
S4	Bottom 6	3023.4	0.0 0.0	1045.6 34.6	881.9 29.2	559.5 18.5	503.6 16.7	32.2 1.1	0.6 0.0	0.0 0.0
S5	Spoil 6	3642.5	0.0 0.0	2603.2 71,5	721.0 19.8	244.1 6.7	67.5 1.9	6.4 0.2	0.3 0.0	Trace 0.0
S6	Bottom 9	2618.3	32.3 1.2	1434.4 54.8	365.0 13.9	312.5 11.9	351.9 13.4	112.9 4.3	8.9 0.3	0.4 0.0
S7	Spoil 9	3476.6	201.1 5.8	1748.7 50.3	690.4 19.9	528.8 15.2	275.2 7.9	32.3 0.9	0.1 0.0	Trace 0.0
S8	Bottom 12	3010.4	392.6 13.0	2032.3 67.5	364.5 12.1	126.2 4.2	70.5 2.3	23.1 0.8	1.1 0.0	0.1 0.0
S9	Spoil 12	3915.2	669.8 17.1	2177.4 55.6	474.9 12.1	331.2 8.5	199.7 5.1	61.0 1.6	1.2 0.0	Trace 0.0

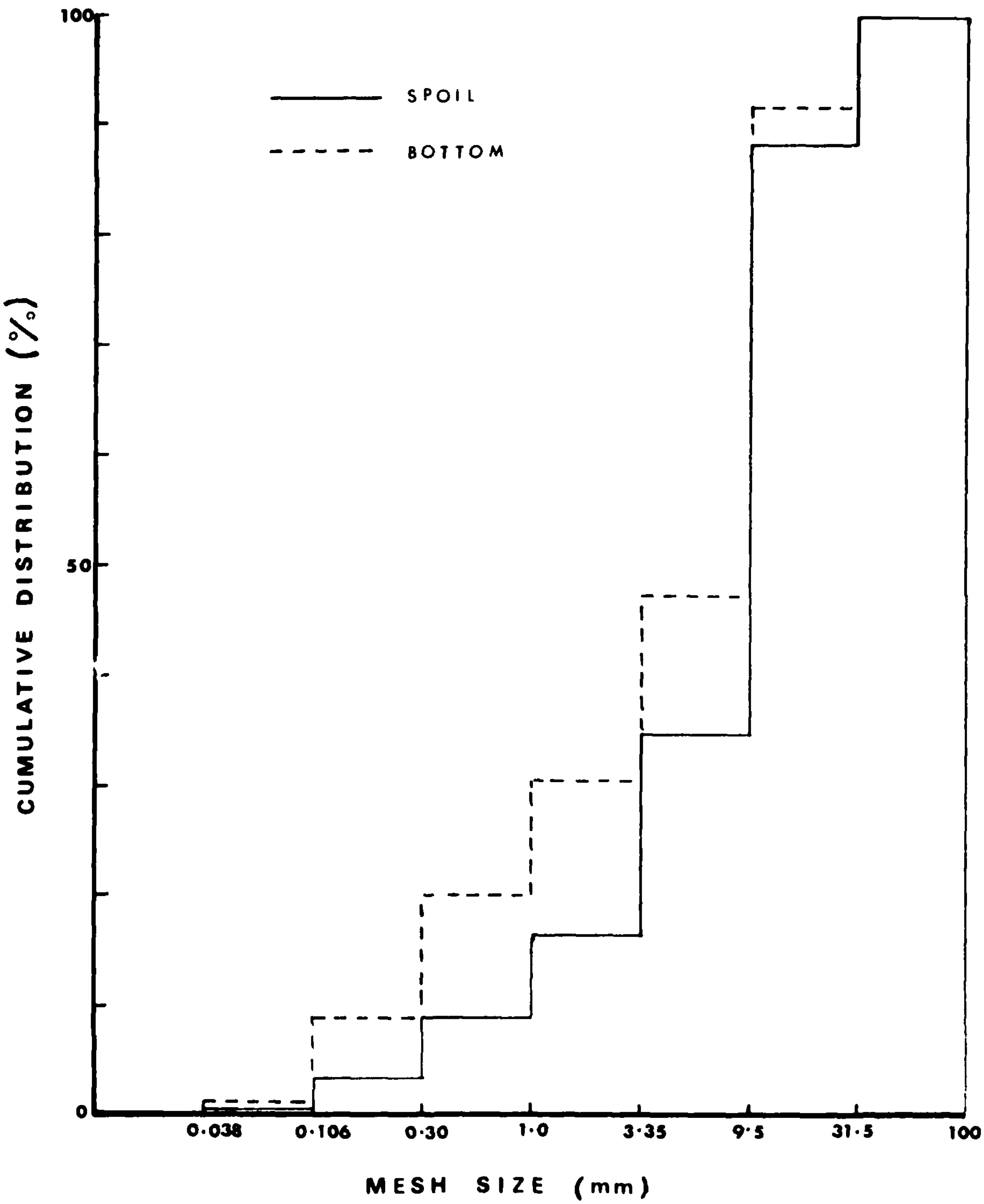

Figure A1. Comparison of the cumulative distributions of gravel sizes between samples from the spoil and from the bottom of the trenches.

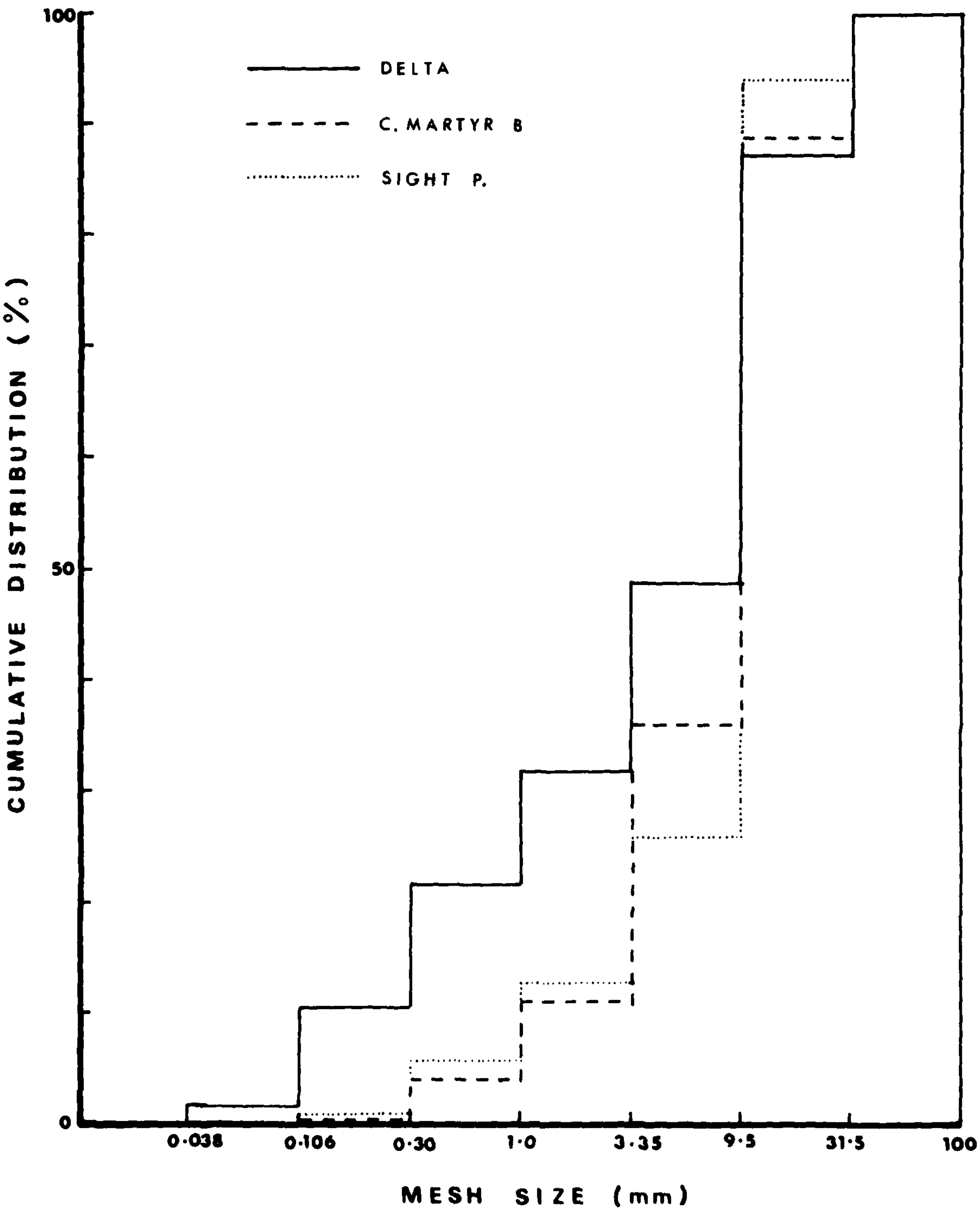

Figure A2. Comparison of the distributions of gravel sizes from three different stations.

APPENDIX 'B'

STEREOPHOTOGRAPHY

STEREOPHOTOGRAPHY

We took a number of stereo pairs of photographs at the test sites to assist in interpreting measurements and notes made in the field. The camera used was a Konica Aerial Camera Type G fitted with an f 3.5, 135 mm lens adapted to clamp on either end of a bar to obtain a 1 m spacing (Figure B1). The film used was a Kodak Type CPS 120 Colour negative and 85 mm square prints were made for examination. In most cases the photographs include a 1 m side square frame to assist in estimating dimensions.

The bar was clamped to a standard survey tripod and levelled before taking photographs. Over the ranges required at the test sites (20 to 200 m), the 1 m separation gives good stereo resolution without undue eye strain. Examples are given in Figures B2 and B3.

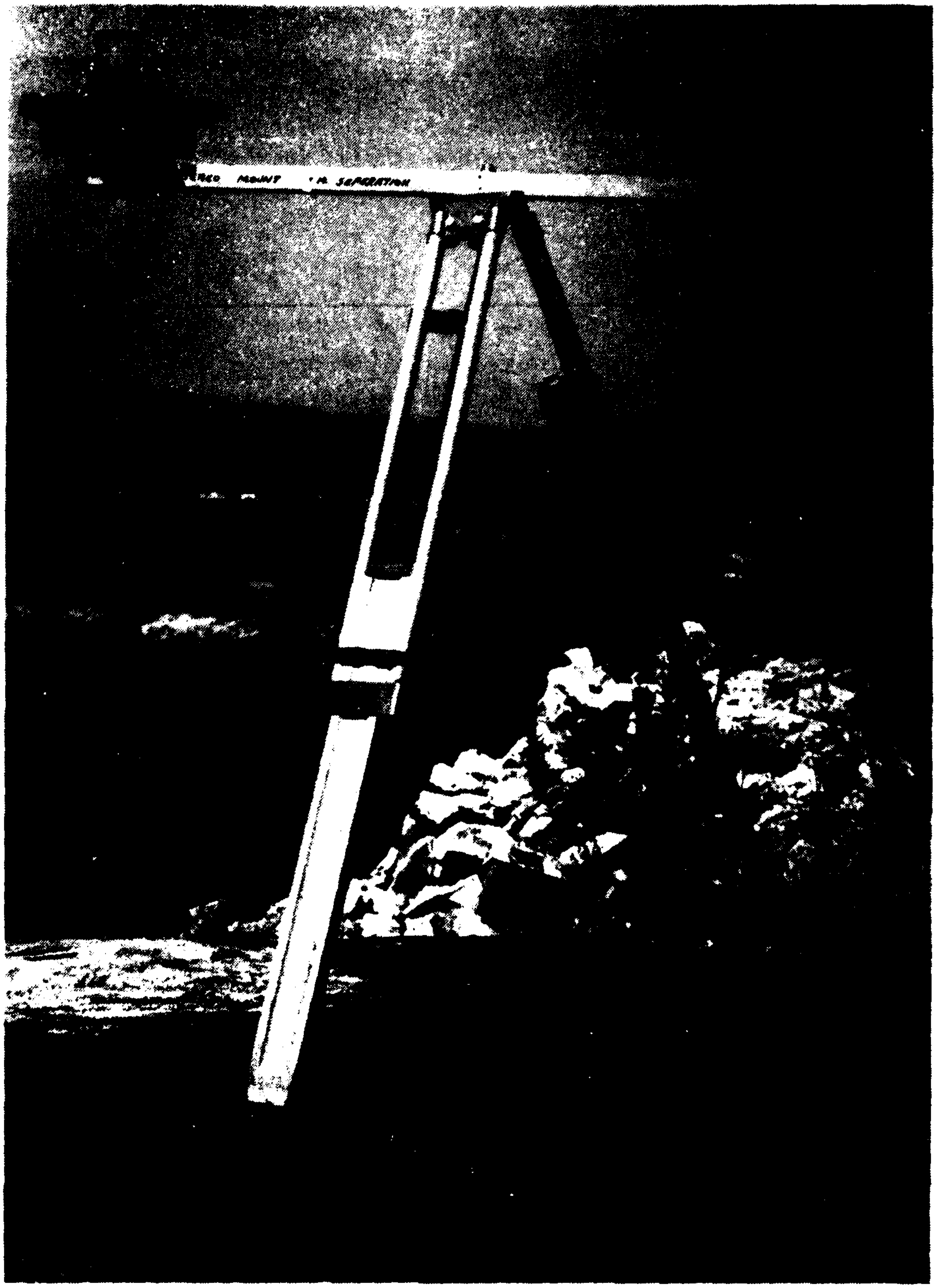

Figure B1. Arrangement for stereophotography. The 1 metre bar is a square aluminum tube which provides sufficient rigidity when the camera is moved from one to the other.

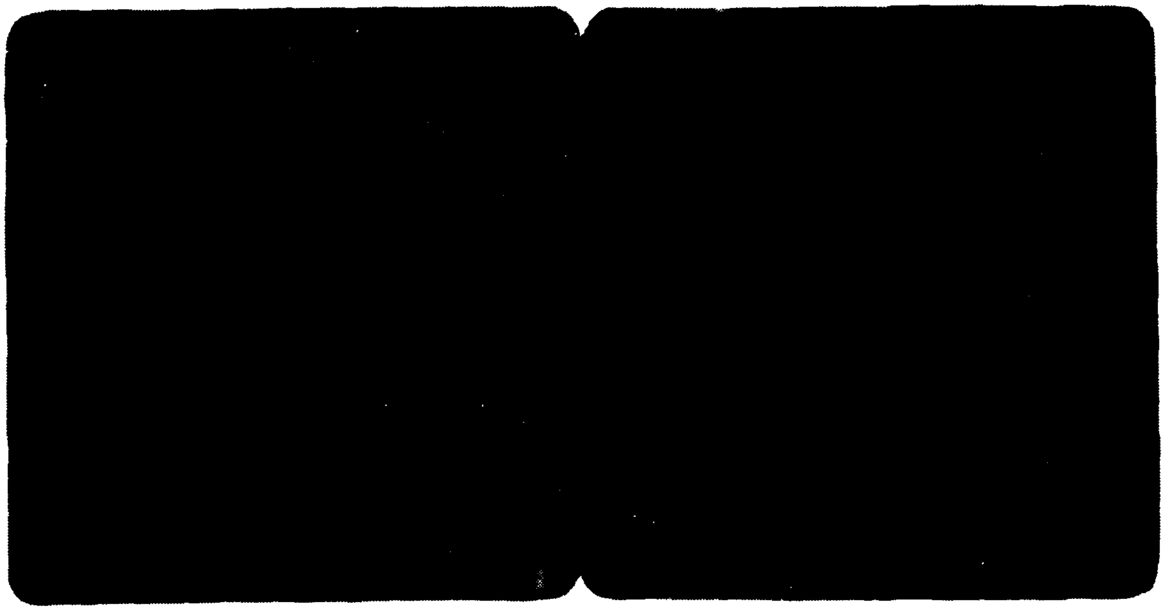

Figure B2. Stereo pair of gravel strip discussed in Appendix C.

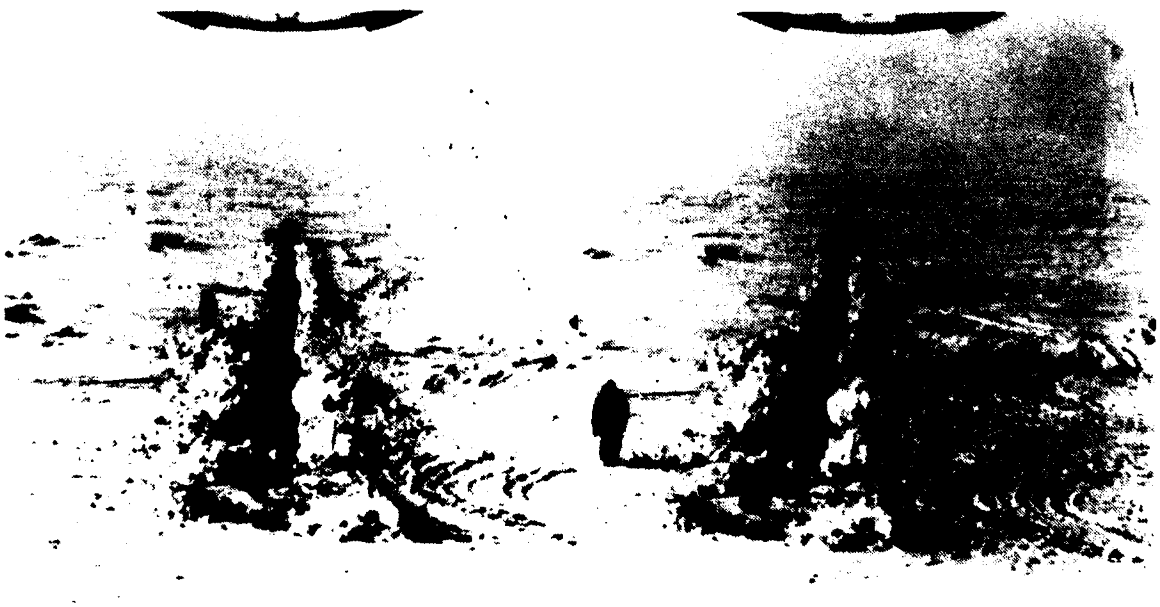

Figure B3. Stereo pair of trench at Cape Martyr A, May 1978 from a position 30 m up the hillside.

APPENDIX 'C'

ABLATION EXPERIMENT

APPENDIX C

ABLATION AND ICE DUSTING

A number of experiments have been reported in which some kind of material with a low albedo has been spread on the surface of sea ice to increase the spring melting rate. Most of these experiments have been made using carbon black, finely ground coal or similar materials, all of which have to be transported to the area. We carried out a similar experiment using local beach gravel, material which was already at the site and required only to be spread on the ice.

The gravel, taken from the storm berm at the Sight Point Station, consisted of wave washed and sorted shale, half of less than 1 cm diameter, 4/10 between 1 and 3 cm diameter and 1/10 between 3 and 10 cm diameter. The gravel was spread by hand from the back of a low ground pressure tracked vehicle, care being taken to avoid overlapping of the scattered gravel. Figure C1 shows the prepared strip on 29 May 1978, the dimensions being about 100 m x 2 m.

On the next visit to the site, on 2 July 1978, we found that 9/10 of the snow cover and 17 cm of the sea ice had ablated from the gravel covered area; snow melt in the untreated area alongside had caused a 5 cm thick layer of firn to form. The gravel remained fairly evenly distributed although some patches had been washed free (Figure C2). The treated area was now below the freeboard level of the ice sheet and was flooded at high tide. Nine ablation stakes were established on 2 July 1978 and these were scaled at intervals of 4 days until 15 July. The readings showed that during this two week period all the snow cover melted and a mean of 82 cm ablation of the sea ice took place in the treated area, while in the untreated zone the ablation was less than 50 cm.

On 4 August 1978 (Figure C4) we found that the total ablation in the untreated area was now 124 cm leaving only about 80 cm of ice. In the treated area the ice surface was 50 cm below the general ice surface and large holes had developed around the tide cracks. A small boat was used to traverse the treated strip. Finally, on 6 August 1978, the ice cover in the whole of Resolute Bay shifted, displacing the treated strip and terminating the experiment.

As shown in Figure C5 the use of local beach gravel increases the absorption of solar energy and the ablation of the ice. However the amount of extra energy absorbed by the gravel decreases as the ice becomes flooded with melt water or through the periodic tidal flooding with sea water. A scattering of local gravel will accelerate the melting of sea ice and if a few days or weeks advance of ice breakup is important it may well be worthwhile to use this method.

Figure C1. Ablation strip on 29 May 1978, immediately after laying the gravel. The strip is about 100 m long and 2 m wide.

Figure C2. Section of the gravelled surface on 4 July 1978. The frame is 1 m on a side. The layer of firm at the bottom of the snow layer in the untreated area is about 10 cm thick.

Figure C3. View of the gravelled strip from the beach end on 4 July 1978. Ablation stakes were set both in the treated and untreated areas.

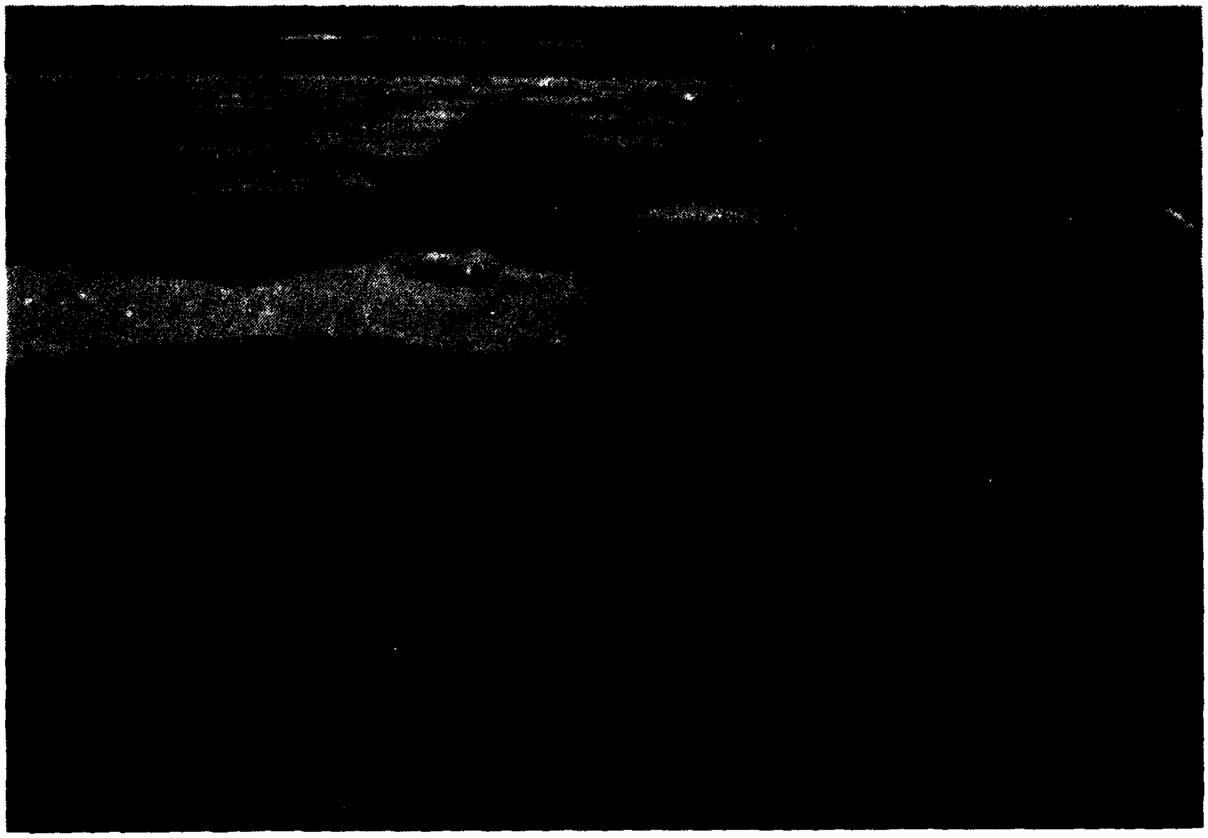

Figure C4. View of the treated strip on 4 August 1978.

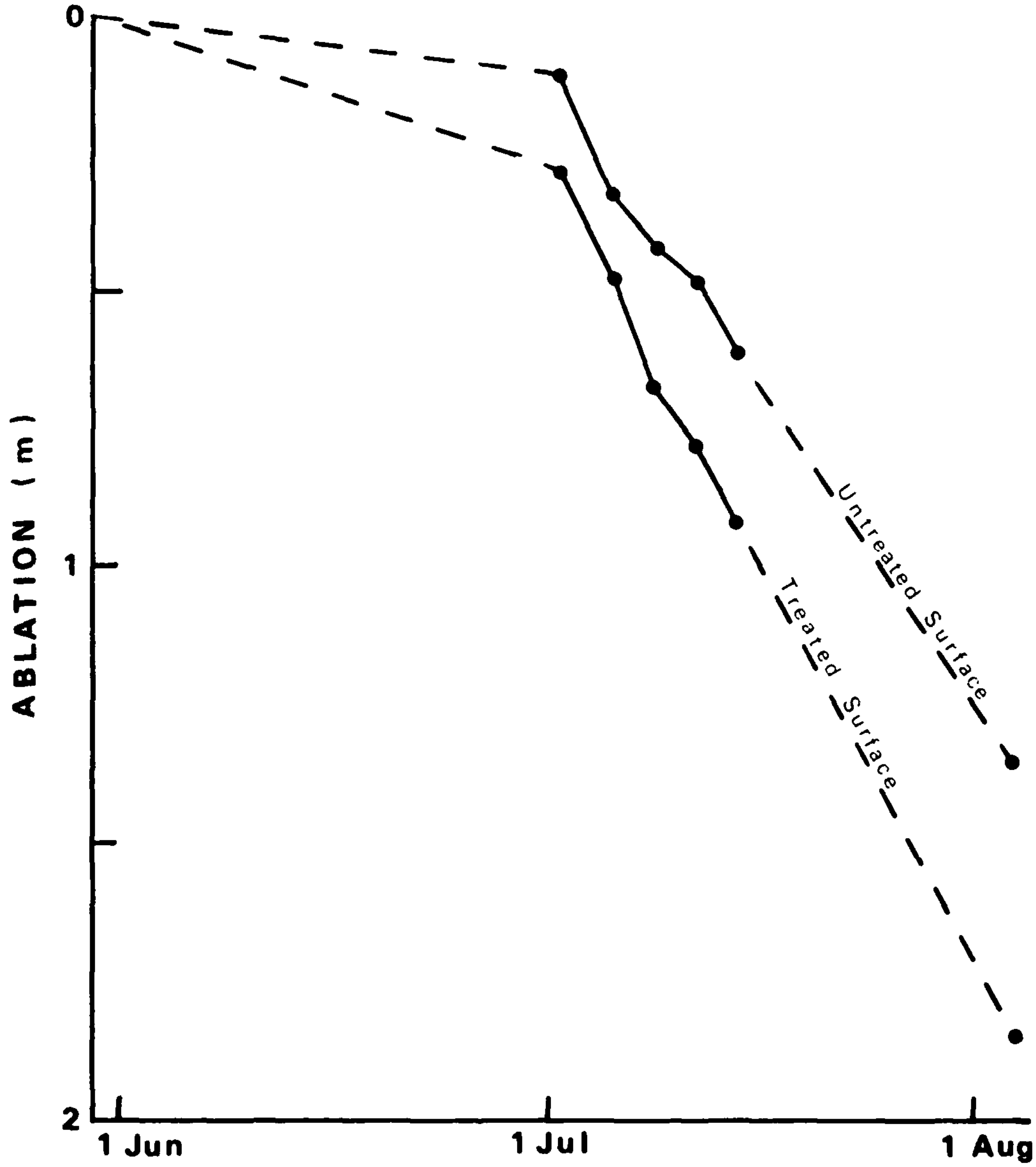

Figure C5. Comparison of the ablation on the treated strip and on the ice alongside.

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Arctic Ice

Underwater cables

Physical properties of ice

Ablation

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13. ABSTRACT

This was a preliminary investigation into the physical processes in the beach zone along an arctic coast with emphasis on the possible damage to scientific equipment by ice action on gravel beaches. Detailed profiles are given of the spring ice on a number of beaches in the area and of the bathymetry and ice morphology at three stations where test cable arrays were laid. The results indicate that a comparatively shallow trench into the frost table below the beach will provide good protection for cables laid across gravel beaches, and that most of the breaks to be expected are probably due to the freezing of the cable onto the bottom surface of the sea ice during tidal changes in level. Additional investigations were made into methods of accelerating the melting of sea ice, on a simple method of obtaining stereophotographs and on the properties of a belt of fresh-water anchor ice which was found along the beaches.

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